SoRI-EAS-86-465

RECOMMENDED METHODOLOGY FOR THE DETERMINATION OF PARTICLE SIZE DISTRIBUTIONS IN DUCTED SOURCES

PROJECT FINAL REPORT

May 1986

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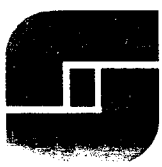
THE CALIFORNIA AIR RESOURCES BOARD

ARB Contract A3-092-32



Southern Research Institute

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FOREWORD

Broadly speaking, one can divide the ARB current or potential needs with respect to particle sizing into three classes: (1) regulatory, including setting of emission standards and compliance testing; (2) control strategy development (emission inventories) and permitting (control device selection, etc.); and (3) basic research and development. Of course, considerable overlap exists in the types of information needed for each of these activities.

As currently foreseen, possible regulatory action on emissions may take place based on one or both of two particle size classes. The first, and more likely, of these possible regulatory actions is related to the PM_{10} class (particles having aerodynamic diameters smaller than 10 μm) for which a state ambient air regulatory standard has already been set. The second class for possible action concerns fine particles, those particles having aerodynamic diameters smaller than 2.5 μm. In either case, the regulations may be chemical species and/or industry or process specific as well as particle size specific. If particle size specific regulations are set, compliance test methods would be a concomitant necessity. Development of an emissions inventory would be a preliminary activity prior to such regulatory action - such an inventory is currently being constructed within the ARB for the PM_{10} class based on such information as is now available. The number of size classes (and the resolution) required for these activities is obviously limited - only one or two size cuts are needed and relatively simple and inexpensive techniques are desirable if they are to be used as compliance tools.

Greater resolution than that needed for compliance testing is desirable for activities related to permitting. The performance of many (or most) particulate control devices can be predicted for a given source from a broad base of experimental data and models provided that the gas stream conditions and the particle size distribution of the material to be collected are known. In most cases, the critical size range for estimating the probability of achieving a required level of control in this fashion is from about 0.1 μm to 20 μm. Resolution into about eight size classes, evenly spaced in terms of the logarithm of particle diameter, over the latter range is generally sufficient. In some instances specific target chemical species are of interest which may not be homogeneously distributed with respect to particle size. In those cases, size segregated samples suitable for chemical analysis may be needed in addition to data for overall size distribution. Three to five size fractions may be adequate for this application.

The needs of the agency with respect to basic research presently fall into three areas. The first is providing support for the activities previously described; the second is the development of a data base characterizing the principal types of industrial emissions in the state; and the third is concerned with particulate chemistry. At present the main concerns in the area of particulate chemistry are primarily emissions of toxic substances and substances which act as catalysts in secondary aerosol formation.

This document serves as the project final report for ARB Contract A3-092-32. Under this contract three proposed sizing methods were selected and documented: (1) Source PM_{10} Method, (2) Size Distribution Method, and (3) Sized Chemical Sample Method. This report describes the Performance Specifications, Methods Review, and Equipment Selection for each of the three methods. Separate Procedures Manuals were prepared for each of these recommended methods. Each of these manuals includes discussions of the basic operating principles for the selected equipment, a field protocol, and a detailed data analysis procedure. These manuals are provided as attachments to this report. This document presents brief summaries of the three procedures manuals and a discussion of the field demonstration conducted at ARB's Sacramento offices in January, 1986.

ABSTRACT

This report serves as the project final report for ARB Contract A3-092-32. Under this contract three proposed sizing methods were selected and documented: (1) Size Distribution Method, (2) Sized Chemical Sample Method (Method for Obtaining Size Fractionated Samples for Chemical Analysis), and (3) Source PM_{10} Method (Method for Obtaining Size Specific Stationary Source Particulate Information Using the Emission Gas Recycle Technique). This report describes the Performance Specifications, Methods Review, and Equipment Selection for each of the three recommended methods. Separate Procedures Manuals were prepared for each of the three proposed methods. Each of these manuals includes discussions of the basic operating principles for the selected equipment, a field protocol, and a detailed data analysis procedure. These manuals are included as attachments to this report. This document presents brief summaries of the three procedures manuals and a discussion of the field demonstration conducted at ARB's Sacramento offices in January, 1986.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

FIGURES

FIGURES (Continued)

FIGURES (Continued)

Figure

FIGURES (Continued)

Figure

LIST OF TABLES

ACKNOWLEDGEMENTS

This report was submitted in partial fulfillment of ARB Contract No. A3-092-32, "Recommended Methodology for the Determination of Particle Size Distributions in Ducted Sources" by Southern Research Institute under the sponsorship of the California Air Resources Board. Work was completed as of February 28, 1986.

SECTION 1

INTRODUCTION and CONCLUSIONS

This is the final report on Contract A3-092-32, "Recommended Methodology for the Determination of Particle Size Distributions in Ducted Sources". In summary, the project objectives were to provide guidance to the Air Resources Board, or ARB, in the selection of measurement methodologies and equipment for particle size related measurements of ducted (stationary) sources, to document the performance of the selected methods, to provide complete protocols for sampling and data analysis, and to provide documented computer-based data reduction programs for the treatment of field results obtained using the selected methodologies. The work on this contract was carried out over the period from July, 1984 through May, 1986 under the direction of the Research Division of the ARB. The effort was coordinated with the Stationary Sources Division of the ARB as that group would be one of the primary users of the methods.

The major efforts undertaken during the course of the contract were the following:

Review of the needs of the ARB with respect to size related particulate sampling at stationary sources.

Development of specifications for the methods and equipment to meet the needs identified above.

Review of available methods which might be applicable and selection of candidate methods.

Characterization of the selected methods in terms of operating principles, theories, and empirical performance.

Development of field sampling protocols for the application of the methods.

Development of data reduction protocols and computer programs for data analysis and reporting.

Provision of a field demonstration of the methods for the ARB and other interested parties at the discretion of the ARB.

The work was carried out in two phases. The first phase involved determining the needs of the ARB, generating specifications for the methods, reviewing available methods, and finally, selection of the proposed methods. The second phase consisted of indepth analyses of the selected methods with respect to their theoretical bases, their empirical performance, known problems and interferences, development of field protocols for their application, development of the data reduction protocols and programs, and demonstrating the selected methods to ARB personnel. Summaries of the efforts in each of these areas are given in this report. The background information, field protocols, and data analysis protocols and programs for each of the three proposed methods

finally selected are provided in separate documents, one for each method, as attachments to this report.

Conclusions

Three identifiable current and future needs with respect to particle size related sampling of stationary sources were found. These were as follow:

1) A method for obtaining particle size distribution information for satisfying needs related to emissions control and downwind transport.

2) A method for obtaining size fractionated samples in sufficient quantity to permit chemical analysis for identifying the particle size fractions in which certain toxic, hazardous, or other environmentally significant elements or compounds might be concentrated.

3) A method for measuring PM_{10} emissions from stationary sources in support of the ambient PM_{10} regulations and possible PM_{10} source regulations.

Inertial sizing using cascade impactors was selected as the proposed method for the measurement of particle size distributions. The equipment and protocol provide for measurement in five to eleven size fractions, depending upon immediate goals, over the size range from about 0.1 micrometers to about 15 micrometers. Series (or cascade) cyclones were selected as the proposed method for obtaining size fractionated samples for chemical analysis. The selected equipment and protocol for the latter purpose will provide samples in six size fractions with fractionation points in the range from about 0.25 micrometers to 10 micrometers. Finally, a method was selected for PM_{10} measurements. This proposed method is currently under development by the US EPA. The method uses the technique of emission gas recirculation to provide full flexibility in meeting sampling traverse requirements while maintaining a 10 micrometer particle cutoff diameter and general compatibility with the current Method 5 for particulate sampling.

SECTION 2

PERFORMANCE SPECIFICATIONS, METHODS REVIEW, AND EQUIPMENT SELECTION FOR THE ARB SIZING METHODS

2.1 Summary of Agency Needs

The particulate sizing needs of the ARB were reviewed and assessed using: the original request for proposal on which the contract was based, a meeting with personnel of the ARB in Sacramento, a meeting with personnel of the South Coast Air Quality Management District, and a telephone survey of various ARB personnel and its contractors. The purpose of the review was to define a set of performance criteria on which to base the selection of particulate sizing methods for application mainly by the ARB, but it is expected that local air quality management districts, industries, and consulting firms within the state of California will also become users of the proposed methods as well. As determined from the meetings and surveys, potential end uses of the data to be obtained by the particle sizing methods include basic research regarding source emissions, potential health and toxicity effects related to specific elements and compounds which might be concentrated in particular ranges of particle size, development of particle size related emission inventories, and possible compliance methods for potential particle size related emission standards (e.g. PM_{10}). It was anticipated that three or four judiciously selected methods would cover the bulk of the agency's particle size related sampling needs.

The more important factors to be considered in the review included such items as the sizing ranges and resolutions needed to accomplish the goals of various parts of the agency, the particle size conventions that were most appropriate for the agency's applications, possible needs for chemical analyses of size-fractionated particulate matter, and condensable and/or reactive components of the gas streams. Other items to be considered in arriving at the specifications were such things as test duration (sampling time and number of samples required) that might be needed to characterize a source, ease of handling of equipment, applicable concentration range, ease of sample recovery, applicable range of source conditions, interferences, and accuracy.

Broadly speaking, one can divide the ARB current or potential needs with respect to particle sizing into three classes: (1) regulatory, including setting of emission standards and compliance testing; (2) control strategy development (emission inventories) and permitting (control device selection, etc.); and (3) basic research and development. Of course, considerable overlap exists in the types of information needed for each of these activities.

As currently foreseen, possible regulatory action on emissions may take place based on one or both of two particle size classes. The first, and more likely, of these possible regulatory actions is related to the PM_{10} class (particles having aerodynamic diameters smaller than 10 μm) for which a state ambient air regulatory standard has already been set. The second class for possible action concerns fine particles, say those particles having aerodynamic diameters smaller than 2.5 μm. In either case, the regulations may be chemical species and/or industry or process specific as well as particle size specific.

If particle size specific regulations are set, compliance test methods would be a concomitant necessity. Development of an emissions inventory would be a preliminary activity prior to such regulatory action - such an inventory is currently being constructed within the ARB for the PM_{10} class based on such information as is now available. The number of size classes (and the resolution) required for these activities is obviously limited - only one or two size cuts are needed and relatively simple and inexpensive techniques are desirable if they are to be used as compliance tools.

Greater resolution than that needed for compliance testing is desirable for activities related to permitting. The performance of many (or most) particulate control devices can be predicted for a given source from a broad base of experimental data and models provided that the gas stream conditions and the particle size distribution of the material to be collected are known. In most cases, the critical size range for estimating the probability of achieving a required level of control in this fashion is from about 0.1 μm to 20 μm. Resolution into about eight size classes, evenly spaced in terms of the logarithm of particle diameter, over the latter range is generally sufficient. In cases in which specific target chemical species which may not be homogeneously distributed with respect to particle size are of interest, size segregated samples suitable for chemical analysis may be needed in addition to data for overall size distribution. The size resolution for this application need not be as great - three to five size fractions may be adequate.

The needs of the agency with respect to basic research at the present time appear to fall into three areas. The first is providing support for the activities previously described; the second is the development of a data base characterizing the principal types of industrial emissions in the state; and the third is concerned with particle chemistry. The main concerns in the latter area appear to be primary emissions of toxics and emissions of catalysts which may play roles in secondary aerosol formation.

2.2 Specifications (Performance Criteria)

In this section we have subdivided the specifications by usage rather than attempting to generate a uniform set of requirements for all sampling methods. Some specifications can be listed which are general to all sampling requirements. These general specifications are dealt with first. In addition, we have separately presented recommended specifications on which to base the selection of methods for each of three classes of measurements: (1) PM_{10}, (2) moderate to high resolution particle size distribution measurement, and (3) sampling for chemical analysis of size fractionated material. Separate specifications are better suited for purposes here since the requirements for each of these classes are different and in some cases conflicting. Further, the subject of condensables is treated separately since problems related to them will probably require special treatment(s) in a fashion(s) that can be applied in common to all of the three particle sizing methodologies. In developing these specifications, we have attempted to confine them to properties that will insure that the methods finally selected will be optimal for ARB's purposes without making them so unduly restrictive that little likelihood would exist of methods existing that could actually achieve them.

First, it is necessary to clarify the nomenclature used for defining particle diameter. A number of conventions are used as bases for the presentation of particle size distributions with respect to both the definition of particle size and the property of the distribution presented. Particle size is most often defined in terms of a "diameter" implying that the particles are being treated as spheres - this may be rigorously true or only a useful approximation depending upon the circumstances. The most frequently used diameter bases in air pollution work are:

True diameter - the actual diameter of the particle. Useful only if the particles are spherical.

Stokes diameter - the diameter of a sphere of the same density and settling velocity in air as the particle in question. (Equals the true diameter of spherical particles). This definition is often used as an approximation for estimating the volume or surface area of irregular particles.

Aerodynamic diameter - the diameter of a unit density sphere which has the same settling velocity in air as the particle in question.

Volume equivalent diameter - the diameter of a sphere having the same internal volume as the particle in question.

Surface equivalent diameter - the diameter of a sphere having the same total surface area as the particle in question.

Area equivalent diameter - the diameter of a sphere having the same projected area as the particle in question.

While no set conventions exist for selecting the diameter basis for data presentation, certain bases are favored for use in particular applications. For instance, the aerodynamic basis is the preferred choice in work related to inhalation and health effects and in wet scrubber technology; while the Stokes diameter is favored for work related to light scattering (opacity) and in electrostatic precipitation. In most cases, convenient transformations exist for changing from one basis to another, however, this may not be the case if the particles are highly irregular in shape. Because of their widespread use in research related to health effects, visibility, and control device technology, the methods best suited to ARB's purposes will be those for which the natural diameter bases are either aerodynamic or Stokes.

2.2.1 General Specifications

The conditions under which industrial source sampling are carried out in themselves dictate certain specifications which will be shared in common for all methods to be selected. Among these are features related to portability, support services required, operational temperature limits, corrosion resistance, the sampling platform and port dimensions required, and applicability over the range of particulate concentrations expected for industrial sources. These common specifications are as follows.

1. Provide a measure of total particulate loading.

2. Provide usable samples from sources having any concentration within the range from 0.005 to 50 grains per cubic foot.

3. Provide measurement of the weight fraction of particles smaller than any (the) specified size to within 10 percent of the stated size, with 95 percent confidence.

4. Be applicable in stacks having -5 to +20 inches of water pressure differential to ambient.

5. Be applicable at sources having stack gas temperatures in the range of 0 to 450° Celsius.

6. Be capable of obtaining a representative sample from stacks having gas velocities in the range from 10 to 100 feet per second.

7. Have a maximum single component weight of 50 pounds.

8. Be resistant to corrosion by acids and alkalis.

9. Require port dimensions no larger than four inches in diameter. (Three inches preferably.)

10. Be capable of traversing the stack.

11. Require no greater electrical service than that needed for EPA Method 5.

12. A maximum length of any single component of six feet (probe excluded).

Devices meeting these specifications are man-carryable, amenable to use in the normal physical environment under which source tests must be carried out, and capable of withstanding exposure to the (frequently) hot, corrosive stack gases. The velocity and traversing requirements are necessary in order to insure that representative samples can be obtained, even when the particulate matter is stratified within the duct or stack.

2.2.2 Specifications for Source PM_{10} Method

The PM_{10} methodology can be expected to be used by the ARB, local control districts, and industrial and consulting organizations. Because the method is to be developed ultimately in support of the California PM_{10} ambient air quality standard, which is based on aerodynamic classification, the aerodynamic diameter basis is appropriate for it as well. If it is to be used as a compliance method, it should be applicable by personnel having the same level of expertise as is currently required for ARB Method 5. The method should be modeled after ARB Method 5, except that the sampling nozzle be followed immediately by an inertial collection device having an efficiency of 50% at an aerodynamic diameter of 10 µm. Deviations from Method 5 should be limited wholly to those required to achieve the 10 µm size cutoff. The sharpness of cut of the collector should be such that its collection efficiency curve when plotted in log-probability coordinates has a geometric standard deviation less than or equal to 1.7. The latter value matches that specified for ambient PM_{10} samplers.

2.2.3 Specifications for Size Distribution Method

Moderate to high resolution particle size distributions are needed in research applications of ARB and for use as a basis for estimating expected efficiencies of control devices for control device selection and permitting. Experience has shown that for most applications the critical range over which size distribution data is needed is from about 0.2 µm to 10 µm, together with total concentrations for the ranges smaller than 0.2 µm and larger than 10 µm. Sufficient resolution for modeling the effects of control devices, estimating overall control device efficiencies, predicting stack opacities (for noncondensing stacks), and characterizing the fractional collection efficiencies of operating control devices can be provided by separating the aerosol particles into about six to eight size classes within the 0.2 µm to 10 µm size range. The latter range also includes "respirable" particles and consequently is of special importance in health effects. The actual size distributions of most natural and industrial aerosols are such that they can best be described by distribution functions in which the logarithm of the diameter is the argument (for instance the log-normal distribution). Thus the resolution specification for the method can best be given in terms of log (diameter). Size fractionation at steps of 0.25 to 0.333 in log (diameter) over the 0.2 to 10 µm range is expected to be adequate for most foreseeable needs of the ARB and other potential users of its methods. The sharpness of cut provided by the classifier(s) should result in separation efficiency curves having geometric standard deviations of less than 1.5. The size fractionation must be well characterized with respect to performance changes produced by changes in operating conditions.

2.2.4 Specifications for Sized Chemical Sample Method

At present the needs regarding size fractionated material for chemical analysis fall almost entirely in the area of basic research, and more especially in the area of research on primary emissions of toxic materials and priority pollutants. Interests in toxics include metals (e.g. chromium, beryllium, and cadmium), PAH's, and dioxins and furans. In the case of the

metals, concentrations within specific valence states are sometimes of greater importance than just the total concentrations (e.g. chromium). Aside from toxics, materials which can serve as catalysts for chemical transformations and in the formation of secondary aerosols are of interest.

Discussions of sampling for chemical analysis will be broken into two parts. The first, to be covered here, is comprised of sampling for materials that are in solid or liquid form at stack conditions. However, many toxics - both metals (e.g. arsenic, selenium, and mercury) and organics - are materials which can have substantial vapor phase concentrations at flue gas conditions. Treatment of sampling for analysis of condensables will be deferred to a following section devoted exclusively to the subject of condensables.

The number of size fractions needed to meet the goals of the various potential users of this methodology is somewhat less than that needed for the particle size distributions. The need to collect sufficient material in each selected fraction to satisfy the analytical needs makes it desirable minimize the number of fractions and thus maximize the amount of material in each fraction. Obvious cut points for analysis are the fine (2.5 μm) and PM_{10} (10 μm) fractions for health effects research. Isolation of a frequently occurring submicron combustion mode is desirable, indicating the need for a cut near 0.25 μm; and those in the ARB interested in studies of catalysts have indicated a desire for a cut at 1 μm. A sharpness of cut specification of 1.7 or less for the geometric standard deviation in the efficiency curve should be suitable here.

The sample must be collected in an unadulterated, contaminant free form if valid analyses are to be obtained. Discussions with personnel at analytical laboratories who have provided analyses of particulate matter for the ARB in the past revealed that sample quantities substantially larger than a few milligrams are needed for many, if not most, of the analyses which they have been called upon to perform. Therefore the method must be capable of providing sample quantities in the tens or hundreds of milligrams for the individual size fractions.

2.2.5 Specifications for Condensables Method

The term condensables as used here includes all materials which are wholly or partially in the vapor phase at stack conditions but will be driven to be attached to particles by thermodynamic processes upon discharge to the atmosphere. Thus any material which becomes attached to the particulate matter by condensation, sublimation, prompt reaction, or sorption is considered part of the condensables.

The transfer of material to and from the vapor and solid/liquid phases is a complex dynamic process for which the rates and equilibria depend on the concentrations, temperatures, and mixing rates of the stack gases and the ambient air. Rigorous duplication of the actual plume conditions, even at a single defined set of atmospheric conditions, including matching of mixing rates, mixing ratios, etc. becomes a practical impossibility. Therefore the development of a usable method for sampling condensables will require that a number of compromises be made in order to obtain a workable approximation of plume conditions.

The simplest method for sampling condensables is that used in the California Method 5, in which the condensables are defined as the material collected in bulk in chilled liquid filled impingers. This choice serves a useful regulatory purpose in that the Method 5 "back half" is not likely to underestimate the total condensable emissions. However, this method cannot provide information regarding the ultimate distribution of the collected materials with respect to particle size, nor can it provide accurate data on material which would attach to the particles by sorption as most of the condensation takes place on surfaces other than those of the particles. Further, by placing the collected material in liquid solution or suspension, it becomes possible for reactions to occur which might not take place if the materials had condensed or sorbed on the surfaces of particles in the atmosphere. Therefore impinger collection is not a useful technique for applications in which it is important to determine the effects of condensable vapors on the size distribution of the final aerosol, or for applications in which it is necessary to apportion the condensable contribution to specific size classes. For these applications, we recommend that sampling methods utilize a form of air dilution which simulates the mixing processes that take place in the plume. Suggested specifications for a condensable materials sampling method are:

1. Dilution of a flue gas sample stream with conditioned ambient air be used to simulate the plume processes.

2. A standard dilution condition be used for all sources (e.g. 25:1 dilution ratio, with filtered dilution air at 25° C and 40% RH).

3. The sampling system be capable of being interfaced with currently used ambient air particle sizing and collection devices.

2.3 Final Recommendations for the Number and Types of Methodologies to be Developed

In summary, a total of four sampling methodologies appear to be needed. The first method would be intended to support PM_{10} regulatory work and would provide size fractionation at only 10 μm with the method being generally consistent with current total particulate methods. The second methodology would cover the entire size spectrum but provide detailed information only within the range from about 0.2 μm to 10 μm. That range being the most critical for health effects studies, control device selection and evaluation, and opacity/visibility related work. The third method would be intended to provide fairly large samples, with less size resolution, for chemical analysis. And finally, the fourth method would provide a means of quantifying the contributions of condensibles in as realistic a fashion as circumstances permit short of calling for actual sampling in plumes.

After these recommendations were submitted, a project review meeting was held at the ARB offices in Sacramento. The result of this meeting was a concensus that the first three methodologies described above should be pursued further. However, development of a condensibles method would be deferred and such a method would not be developed on this contract.

2.4 Review of Particle Sizing Methods and Equipment

Task 2 of the project called for a literature survey of potentially relevant sizing methods and associated commercial instrumentation using the respective methods. This survey was conducted independently of the establishment of the performance criteria in order to compile a comprehensive list of all possible approaches to the source measurement problem. A summary of the information gathered in the literature survey is given in the Appendix. In Section 2.5, the criteria are applied to the results of the literature survey and used to select recommended test methods and instrumentation for each of the three specified ARB Methods: (1) Source PM_{10} Method, (2) Size Distribution Method, and (3) Sized Chemical Sample Method.

The instrumentation listed in the Appendix includes equipment which was not designed for in-situ operation but which may be used either for off-line analysis or in conjunction with a sample extraction/dilution system. The tables incorporate an "Instrument Use Code" which identifies the environment in which a particular item of equipment is to be used. In many cases, the measurement principle used by an instrument may be adaptable to more than one environment but in practice we usually find that any given device has been designed to function in only one environment. In some cases, other devices may be available which implement this sizing method in other environments. A general review of the techniques used for particle sizing is given in the following paragraphs.

2.4.1 In-situ Systems

A desirable attribute for any candidate sizing technique is that the size determination be performed in the flue at actual conditions of temperature, pressure, moisture, and gas composition, thus avoiding potential alteration of the aerosol prior to measurement. Four different sizing techniques have been adapted to this in-situ environment: two inertial techniques (cascade impactors and series cyclones) and two optical techniques (single particle scattering by aerosol particles and Fraunhofer diffraction).

The cascade impactor is the most widely used in-situ sizing method and is the method recommended for use as the ARB Size Distribution Method. Cascade impactors in their current commercial form are labor intensive devices which yield data representing time averages for the sample period (a few hours for low concentrations). The device works by pulling flue gas into the sampler at a constant flow rate and then subjecting this sample gas stream to an abrupt change of direction. An impaction surface, or substrate, is located such that the inertia of any given particle determines whether it will follow the gas stream or impact on the surface. The gas stream cascades through several such stages, each one being more abrupt than the previous, thus larger particles impact in the upper stages and smaller particles impact in the lower stages. A filter located behind the last impaction surface removes any remaining particulate matter. Analysis involves determining the sizing properties of the various stages and the weight gains for their respective substrates. This weight gain is determined by weighing the substrates before and after the run, thus the amount of gas sampled (sample volume) must be sufficient to obtain measurable weight changes for all the substrates. The data thus obtained

represents the average size distribution for the sampling period. Various impactors have been designed for ambient measurements which utilize automated techniques for determining the substrate weight changes but these instruments have not been adapted to the in-situ environment, consequently application of the automated devices for industrial sources requires the use of sample extration and conditioning systems so that the aerosols presented to the device(s) are essentially at ambient conditions. The performance of an automated system then becomes limited by the losses associated with the sample extraction and conditioning systems.

Optical devices provide real time sizing information but the sizing information obtained is in terms of light scattering equivalent diameter rather than aerodynamic diameter. The relationship between these two diameters is site specific. Correlation involves concurrently running impactors and the optical device at the same test site. Optical devices are desirable if real time analysis is required or if monitoring is to be performed over an extended period of time at the same location but is not normally used as a substitute for impactor runs. Detailed explanations of these sizing methods have been given by Pyle and Smith, 1984 (EPRI CS-3388 January 1984, Fine Particle Measurement Handbook) and Barth, 1984 (Modern Methods of Particle Size Analysis).

Series cyclones are also designed for an in-situ environment. Their operation is similar to that of an impactor in that the inertia of the individual particle is used to separate it from the sample gas stream but this separation is caused by cyclonic action rather than impaction. Consequently light weight substrates are not used and heavier stage weights must be collected to obtain weighable quantities. Cyclones have the distinct advantage that they can collect large quantities of samples (up to several grams) in each cyclone in the set without overloading. For this reason, we have recommended series cyclones as the preferred instrumentation for the ARB Sized Chemical Sample Method. Series cyclones are also been recommended as an alternate methodology for the ARB Size Distribution Method when high concentrations prevent the use of cascade impactors.

2.4.2 Extractive Systems

Only one commercial sizing instrument has been specifically designed for sampling Flue Gas using a non-diluting extraction system. This instrument is the Source Assessment Sampling System (SASS Train). This device effectively provides three size cuts, greater than 3 μm, 3 μm to 1 μm, and smaller than 1 μm. The device incorporates another cyclone which has a cut of 10 μm but the effects of the nozzle and probe make the meaning of its catch problematical.

The other major approach to characterizing a flue gas size distribution is to use a special dilution system which extracts a measured sample gas stream from the flue, usually at a low flowrate, and dilutes it with a higher flow of clean, conditioned ambient air. The ratio of the flows can be adjusted so that the particulate concentration, temperature, and moisture content are acceptable to instrumentation designed for monitoring ambient aerosols. Such an extraction system itself introduces significant particulate losses for particles larger than about 2 μm but line losses for the smaller particles are

generally acceptable. Within these limitations a large number of sampling methods become usable for source assessment. Most of the instrumentation designed for ambient aerosol particle sizing and clean room monitoring may be used with such a dilution system. Methods which can be used for source sampling when applied in conjunction with an extraction and dilution or conditioning system are described in the following paragraphs.

In the Aerodynamic Transport (AT) sizing method airborne particles moving at a constant velocity are introduced into an air stream moving at a higher constant velocity. The particles in the sample stream are thus accelerated. This rate of acceleration is size dependent and is measured with laser velocimetry instrumentation. In this manner, real time aerodynamic sizing information can be obtained over the range of 0.5 μm to 15 μm. Line losses in the extraction/dilution system limit the upper size to about 2 μm for flue gas applications but real time aerodynamic sizing information can be obtained for the 0.5 to 2 μm range. Unfortunately, the technique does not provide cumulative information for particles smaller than 0.5 μm and the concentration information is on a number basis rather than a mass basis. The resolution of the device does, however, permit fairly good conversion from number concentration to mass concentration.

Similar information can be obtained from cascade impactors equipped with automated mass detectors (Quartz Crystal Microbalance). These devices provide real time aerodynamic concentration information on a direct mass basis. Although these automated impactors will not, at present, tolerate in-situ temperatures, these impactors may be used, within the limitations of a sample extraction dilution system, to obtain real time measurements of size distributions.

Submicron particle concentrations can be measured with a condensation nuclei counter (CNC). A CNC does not provide sizing information in and of itself but may be used in conjunction with diffusion batteries to obtain sizing information on a number basis for very small particles. The CNC works by exposing particles to a supersaturated vapor. The particles serve as nuclei for condensation and thus produce large liquid droplets. In this manner the size of the particle is increased, making photometric detection possible. The final droplet size is a function of the supersaturation and is independent of the original particle size. Thus the device provides a direct measure of total concentration, independent of particle size.

A Diffusion Battery (DB) is an assembly of suitable gas passages (narrow channels, fine tubing, or screens) that serves as a size-dependent particle collector. Brownian motion serves as the removal mechanism for the diffusion battery. As the aerosol moves in stream line flow through the channels of the diffusion battery, the random motion of the particles cause them to diffuse to the walls. The rate of this diffusion is predictable and may be calculated as a function of particle size, diffusion battery geometry, and flow rate. When used with a particle concentration detector such as a Condensation Nuclei Counter the combination of instruments may be used to measure particle size distributions over the size range 0.01 μm to .3 μm.

Another means for submicron particulate measurement utilizes electrical mobility of charged aerosol particles. The Electrical Mobility Sizing Technique determines size by a three step process. First, an electrical charge is placed on the particles by exposing the flow stream to a unipolar ion cloud in which ions are attached to the particles. The amount of charge placed on any given particle is size dependent. The particles then pass into a laminar flow precipitator where they are subjected to an electric field of known strength. For a given flow rate, the electrical mobility of a particle and the strength of the applied electric field determine the ability of the particle to traverse the collection region without being captured. A detection device located at the exit of the collection region measures the number concentration of the particles which were not removed by the precipitator. For a given field strength in the collection region, all particles smaller than a specified size will be collected. By increasing this field strength in a series of steps, progressively larger and larger particles may be captured. The change in measured concentration for two different collection voltages is a direct measure of the number of particles in a size range.

Numerous optical techniques have been developed for detecting and sizing particles by means of their light scattering properties. Instruments have been designed which measure the light scattered from single particles at a variety of scattering angles. In these instruments, the intensity of light scattered by a single particle as measured by a photodetector, is related to the size of the particle. Concentration and size distribution information is then obtained by counting the number of particles which produce scattering intensities within preselected ranges. A multichannel analyzer is commonly used to perform this pulse heighth (intensity) analysis. Other optical devices make use of the gross scattering properties of an ensemble of particles using such techniques as Fraunhofer Diffraction pattern analysis (time-averaged light scattering) and Photon Correlation Spectroscopy (time-dependent light scattering). In general, the single particle counters were designed as clean room monitors and are intended for use with aerosols where concentrations are low. The other techniques involving multiple particle scattering were primarily developed for the powder technology industry where it is practical to suspend a powder in a non-soluble liquid and determine its size distribution.

2.4.3 Off-line Systems (Laboratory Only)

Much of the particle sizing instrumentation that is commercially available has been designed for the powder and pharmaceutical industry where particles are handled as bulk powders rather than as aerosols. Consequently, much of the instrumentation requires the particulate to be suspended in a non-soluble liquid or to be redispersed from a bulk powder form to an aerosol form. These sizing techniques are not suitable to in-situ or extractive sampling. Some of these sizing methods have been discussed earlier, namely the optical techniques for gross scattering, Fraunhofer Diffraction and Photon Correlation Spectroscopy.

Perhaps the most common laboratory sizing technique is the use of sieves. This technique is limited to relatively large particles and is mentioned here only for completeness. Particles in the sieve size regime are too large to remain suspended in an aerosol for any significant length of time and are efficiently removed by the most simple of pollution control equipment.

Microscopy is another laboratory sizing technique. Here sizing is performed by making measurements on individual particles as seen by optical, Scanning Electron, or Transmission Electron microscope. Making such measurements by manual techniques can be very laborious. Fortunately, image analysis instrumentation has permitted automatiom of this task. The cost of an electron microscope and associated image analysis system is very expensive, consequently, such measurements are commonly obtained as a testing lab service rather than by user-owned equipment. Computer Controlled Scanning Electron Microscopy (CCSEM) equipment adds morphological classification and elemental composition (x-ray analysis) to the image analysis capability of electron microscopy. The range of sizes which can be covered by a given microscopy technique is limited on one or both extremes, the results are on a number basis rather than mass, and the diameters are not on an aerodynamic basis. As with any laboratory technique, the main question relating to the characterization of an aerosol is "how well does the size distribution of this redispersed aerosol (or suspension) represent that of the original aerosol?"

Centrifugal Separation has been used as the particle sizing method in a number of devices. One such is the Bahco Particle Classifier. In this technique the system spins mechanically and the particles, in bulk powder form, are redispersed by being introduced along the axis of the spinning system together with a stream of air. By changing the flow rate of this stream of air one can control the diameter cut off of particles that are forced to the cylindrical wall of the instrument. The sample retained in the center of the device is then removed and weighed. The weight difference between runs at different flow rates is a measure of the particles in a given size range. Successive runs are made at progressively higher flow rates removing progressively larger and larger particles. The Bahco Technique of centrifugal separation has been selected by the American Society of Mechanical Engineers in their Power Test Codes for Determining the Properties of Fine Particulate Matter. (ASME PTC 28, 1954). Consequently, a very large data base is available on Bahco measurements of samples from a large variety of industrial sources.

Resistivity pulse, more commonly known as the Coulter Counter Principle, is another widely used laboratory technique. In this technique the particles are suspended in a suitable liquid electrolyte. The dilute suspension is passed through a fine aperture in which an electric current has been established. If the electrical conductivity of the particles is different from that of the electrolyte, a change in measured current is registered as a particle passes through the aperture. The magnitude of the change is related to the volume of the individual particle. Pulse heighth analysis is performed on these signals and volume distribution information is obtained. A size distribution is then calculated by assuming the particles to be homogeneous spheres and using a measured or assumed density for the particles.

Sedimentation rates in gases or liquids are also used for particle size analysis. Automated sedimentation analysis is performed by several instruments. Some use x-ray attenuation to determine the sedimentation rate,

others use various optical techniques. To push this technique to lower sizes, the sedimentation has been augmented by centrifugal techniques.

A host of optical techniques have been applied to particles in liquid suspensions. These techniques include single particle scattering at a variety of different scattering angles, (some using white light, others using lasers), light blockage, and gross particle scattering such as Fraunhofer Diffraction and Photon Correlation Spectroscopy.

2.5 Equipment Selection for CARB Particle Sizing Methods

Items of commercially available equipment which satisfied most or all of the performance criteria discussed earlier were identified among all those found in the literature review. These were then evaluated against the performance criteria by the scoring system provided in the Table 2-1. The rankings which resulted were used to make equipment recommendations for each of the four different test methods to be used by CARB: (1) Stationary Source PM_{10} Method, (2) Size Distribution Method, (3) Sized Chemical Sample Method, and (4) Plume Condensibles Method. The final recommendations are summarized in Table 2-2.

2.5.1 General

The key information needed for evaluating the available particle sizing devices is contained in Table A-4 of the Appendix. In general, all of the instruments reviewed can be classified as either ON LINE or OFF LINE, where off line means that the original aerosol has been collected as a bulk sample and must be redispersed in order to perform the desired analysis. The performance criteria preclude the use of redispersion techniques. This restriction eliminated many of the devices and/or methods.

The criterion of sizing on the basis of Aerodynamic and/or Stokes diameters excludes the use of optical devices since data from these can only indirectly be correlated to an Aerodynamic or Stokes diameter. After the application of this criterion, only six instrument types remain. These actually represent only four classes of instruments: Aerodynamic Transport, Cyclones, Diffusion Batteries, and Cascade Impactors. Of these four, only Cascade Impactors and Cyclone Systems are capable of in-situ operation.

Aerodynamic Transport and Diffusion Battery devices would both require sample dilution and conditioning before they can be applied to flue gas measurements. Thus they require the support of a Sample Extraction and Dilution Systems (SEDS). The only SEDS available are prototypes which require about 40 amps of power and weigh in excess of 200 lbs. Traversing capabilities are limited and internal particle losses are very high for particles larger than about 2.0 μm. The requirements for providing submicron particulate mass concentrations and a measure of total particulate loading preclude these categories because these devices directly measure number concentrations and use this information together with some assumptions to calculate mass. The upper size cut off of 0.3 μm for diffusion batteries precludes any measurement of total particulate loading and the Aerodynamic Transport device does not detect

Table 2-1. Summary of Performance Criteria for Particulate Sizing Methods*

I.	General Specifications (Listed below are the percentages to be applied toward the point value indicated in the appropriate method)	
E	A. Diameter Bases: Aerodynamic or Stokes	
	B. Data Output	
E	1. Measure of total particulate loading	
E	2. Measure of cumulative mass smaller than specified size	
5%	3. Actual cuts within 10% of specified size	
5%	4. 95% confidence limits	
	C. Sampling Environment	
35%	1. Concentration limits: 0.005 to 50 gr/ft^3 (0.011 to 110 gm/m^3) Note: Separate instruments may be designated as either low concentration samplers or high concentration samplers.	
E	2. Stack pressure: -5 to +20 inches water gauge pressure	
10%	3. Stack temperature: 32 to 840°F (0 to 450°C)	
20%	4. Stack velocity: 10 to 100 ft/sec (3 to 30 m/sec)	
	D. Hardware Features	
10%	1. Component weight limit: 50 lb (23 kg)	
5%	2. Corrosion resistance: acids and alkalies	
E	3. Port requirement: 4 inch (10 cm)	
E	4. Traversing capability	
5%	5. Electrical power: no more than 1650 watts (15 amp, 110 vac)	
5%	6. Length restriction (probe excluded): six feet (2 meter)	
II.	Source PM_{10} Method (100)	
	A. Aerodynamic Diameter Basis	E
	B. Operator Skill Level: same as CARB Method 5	20
	C. Cut at 10 μm: 50% collection efficiency at 10 μm aerodynamic	E
	D. Sharpness of Cut: $\sigma_g \leq 1.7$	E
	E. Deviation from CARB Method 5: Only as necessary to obtain the 10 μm size cutoff	20
	F. All of the General Specifications Except as Specified Above	40
	G. Potential Interest in a Second Cut at 2.5 μm	20

*This table is provided only as a convenient summary of the criteria given in the Performance Criteria document and is not intended to expand upon or reduce the requirements stated in that document. The point values shown are to be used in the evaluation of candidate instruments for a given method. The symbol E designates a criteria which is essential. If an "E" criteria is not satisfied by a candidate instrument, the instrument is rejected from consideration.

III. Size Distribution Method (100)

A. Size Range
1. Cumulative mass < 0.2 μm — E
2. Range of interest: 0.2 μm → 10 μm — 30
3. Size resolution: 5 to 8 cuts within 0.2→10 μm range, evenly spaced logD (constant ratio), maximum ratio 2.15, minimum ratio 1.63 (delta logD of 0.333 and 0.28, respectively) — 30
4. Sharpness of cut: $\sigma_g \leq 1.5$ — 5
5. Calibrations identified as to configuration: grease, glass fiber, quartz fiber, bare metal, etc. — 5

B. Measure of Total Particulate Loading (ie, includes the "+ 10 μm" fraction) — 10

C. All the General Specifications Except as Specified Above — 20

IV. Sized Chemical Sample Method (100)

A. Size Fractions, Aerodynamic Diameter — 30
1. d < .25 μm
2. .25 - 1 μm
3. 1 - 2.5 μm
4. 2.5 - 10 μm
5. >10 μm

B. Sharpness of Cut: $\sigma_g = 1.7$ — 5

C. Bulk Sample Quantities: 10-100 mg for each size fraction — 40

D. Sample Contamination: Unaltered, contamination free samples — E

E. All the General Specifications Except as Specified Above — 25

V. Total Condensibles Method: Total condensibles information is currently being obtained by CARB Method 5 "Backhalf". This equipment could either continue to be used separately to obtain the total condensibles data or, it could be used as a "Backhalf" to any of the three methods listed above, provided the sampled gas volume is sufficiently large to collect the desired amount of condensibles.

VI. Plume Condensibles Method (not Total Condensibles) (100)

A. Standard Dilution Ratio, Dilution Air Temperature and Relative Humidity: 25:1, 25°C, 40% RH — 50

B. Dilution Air Source: Conditioned Ambient Air — E

C. Instrumentation Interfacing: Ambient Air Particle Sizing Devices — E

D. All the General Specifications Except as Specified Above — 50

Table 2-2. Equipment Selection Summary
Advantages and Disadvantages

Stationary Source PM_{10} Method:

Recommended: Cyclones:
- Advantages: Sharp 10 μm cut, no bounce or overload problems
- Disadvantages: Flow limitations imposed by 10 μm cut, high temperature performance theory not well established

Option: Impactors:
- Advantages: 10 μm data with minimal flow limitations, theory well established
- Disadvantages: Particle bounce, overloading, operator skill level

Size Distribution Method:

Recommended: Impactors:
- Advantages: Good size resolution, light stage loadings
- Disadvantages: Operator skill level, manhour intensive, overloading

Option: Cyclones:
- Advantages: No overloading at high concentrations, simultaneous bulk chemical sample
- Disadvantages: Limited size resolution, require large catches, manhour intensive, high temperature performance not well estabilished.

Sized Chemical Sample Method:

Recommended: Cyclones:
- Advantages: Large bulk sample, contamination free
- Disadvantages: Manhour intensive

Option: Impactors:
- Advantages: Simultaneous size distribution data
- Disadvantages: Light samples only, substrate contamination, operator skill level, particle bounce, manhour intensive

Plume Condensibles Method (with sizing capability):

Recommended: Plume Simulator:
- Advantages: Reasonable estimate at minimal cost, uses ambient instrumentation
- Disadvantages: Operator skill, prototype equipment only

Option: Require Plume Sampling:
- Advantages: Accurate condensibles assessment
- Disadvantages: High cost (airplanes, etc.), limited time in the plume, weather dependency

particles below a 0.5 μm threshold and thus cannot provide a measure of mass concentration for particles smaller than this threshold. Thus only cyclones and impactors remain as potentially useable methods or devices.

2.5.2 Source PM_{10} Method

Hardware

Since the criteria specify a cut at 10 μm it is not permissible to extract 10 μm information from size distribution information obtained by cascade impactors. Cascade impactors also fail to meet the operator skill level criterion. If a single stage impactor were used one would still have problems of overloading. Cyclones are commercially available which can give a D_{50} of 10 μm with a $\sigma_g \leq 1.5$, are simple to operate, and can be followed by a second cyclone to provide an additional cut near 2.5 μm, if needed. Right Angle Impactor Precollectors could potentially be operated at a flow rate that would give a 10 μm D_{50} and not have serious overloading problems, but would be more subject to the effects of particle bounce than cyclones. Cyclones also have the advantage of permitting very large sample catches before overloading. Thus cyclones are the only instruments that satisfy the performance criteria for a single stage PM_{10} Compliance Method.

The Acurex SASS Cyclone System is an extractive system and as such will lose many of the sub 10 μm particles in the sampling lines before they get to the cyclone set. The Gilson device is a liquid suspension system and as such is not acceptable. SoRI developed a Five-Series Cyclone set described in EPA-600/7-78-008 "Development and Laboratory Evaluation of a Five-Stage Cyclone System", January 1978 for the USEPA. Flow Sensor and Sierra (now divisions of the Andersen Group) once independently marketed cyclones of this design. Andersen has recently dropped the Sierra version and now produces only the Flow Sensor version. The InTox cyclone set is also a version of EPA/SoRI Five-Series Cyclone Set. The internal dimensions of all three (Flow Sensor, Sierra, and InTox) are the same as those of the EPA set so that the performance characteristics of all are expected to be those cited in the EPA report. Cyclone 1 of the EPA set will have a D_{50} of 10 μm at typical stack temperatures for flow rates of around 0.5 acfm. Thus, EPA Cyclone 1 followed by a Filter (63 or 47mm) would meet the criteria for the Stationary Source PM_{10} Method. At these same conditions Cyclone 4 of the EPA set will have a D_{50} close to 2.0μm. If desired, EPA Cyclone 4 could be placed between Cyclone 1 and the Filter to gain 2 μm (fine particle) information. Although the individual cyclones are not listed by separate model numbers, Andersen and In Tox do sell these cyclones separately. For operation as a PM_{10} analog of Method 17 the cyclone(s) would be followed by instack filter holders. Suitable filter Holders are available from many vendors. (At high temperatures metal O-rings and quartz filters would be needed.) A Method 5 type sampling train could be used to control the sampling flow rate through the cyclone system. Alternatively, the cyclone(s) could be placed on the entrance to a Method 5 probe and be operated with an out-of-stack heated filter as a PM_{10} analog of Method 5.

Isokinetic Sampling

At this point it is appropriate to mention a secondary sampling problem that is associated with any aerodynamic sizing device when sampling is performed at more than one point in the duct. The problem consists of isokinetic sampling difficulties associated with multi-point traversing using size specific particulate samplers. An incompatability stems from the flow rate dependency of the sizing cut (D_{50}). In order to sample isokinetically at multiple points one must change the sampling device flow rate so that the inlet velocity through the nozzle matches the stack gas velocity at each point. For total particulate emission determinations by Method 5 and Method 17, this requirement of different flow rates at different traverse points does not cause a problem because sizing information is not desired. But when sizing information is to be obtained with an inertial separator, changing the flow rate changes the size separation characteristics during the course of the run. With equipment that is commercially available at present, one has three options: (1) maintain a constant flow rate at each traverse point and accept anisokinetic sampling errors, (2) sample isokinetically and accept smeared cuts in the sizing device, or (3) make multiple single point runs.

One approach to solving the problem is to use a modified traversing protocol (called SIM5 for Simulated Method 5) based on the ideas of constant sample flow rate, multiple nozzles, partial traverses and a maximum permissible isokinetic error. The flow rate needed to obtain the 10 μm cut is determined. The sample plane is then divided into a number of regions which are selected such that the isokinetic sampling errors at any point within them fall within preselected limits. Different nozzles are then used in sampling these regions so that the same sampler flow rate is maintained throughout all the regions. Proper weighting of the emissions from the various zones is achieved by varying the sampling periods used in each. This protocol is adaptable to permit a complete isokinetic traverse to be synthesized when using any fixed flow rate sampling equipment, but can be cumbersome to implement.

A second approach is being pursued currently by the US EPA. In this approach, filtered exhaust gas from the sampler (recycle flow) is added to the sample flow by means of a special mixing nozzle so that the total flow to the sizing device (sample gas flow plus filtered recycle gas flow) is a constant. When a new point is sampled the sample gas flow is set for isokinetic sampling and the filtered recycle gas flow is adjusted so that the sum of the two flows (Total Flow) is held constant. To date this technique has been developed in prototype form only but was the one which was finally selected to propose for use by ARB.

2.5.3 Size Distribution Method

Cascade Impactors are the recommended instruments for the Size Distribution Method. Series Cyclones are an optional alternative. Several of the impactors listed in the Appendix are intended for use in ambient air, hence they should be eliminated from the list as unrealistic for source measurements. Since the criteria establish 0.2 μm to 10 μm as the size range of interest, the two low pressure impactors (Pollution Control Mark 10 and Mark 20B) may be undesirable because of their added expense and complexity. It is recognized that in research situations where submicron particles are of interest these

instruments could be of great value. The Sierra Model 2210 uses only two low pressure stages but operates at 0.1 scfm making sampling times at low concentration sources much longer than that are needed using 0.5 scfm samplers, thus it too is not considered further for general use. Two high grain loading impactors (Andersen HCSS and Pollution Control Mark 8) are listed. These are specially designed for very high concentration situations. They are not readily adaptable to outlet loading situations and, with only four size fractions, do not meet the size resolution criteria. The Zoltec Brink Model C is also specially designed for high loading (inlet) situations, having a very low flow rate. The run time required to collect weighable samples from a clean outlet would be unacceptable with it.

This leaves nine impactors as possible choices: APT, Andersen Mark III, Flow Sensor Mark 3 and Mark 4, Belfort 1502 (MRI), Pollution Control (University of Washington) Mark 3 and Mark 5, and Sierra Models 226 and 228. The Air Pollution Technology (APT) High Temperature High Pressure (HTHP) Impactor was specifically designed for use in sampling a HTHP Fluidized Bed Combustor and is more expensive than the others and offers few advantages other than the ability to be operated at high temperatures and pressures. With the exception of this HTHP impactor the other impactors were designed for lower temperatures where Viton O-rings could be used (<450°F). However, in most cases metal seals can be used, thereby extending the temperature range to the specified 840°F limit. The two Sierra Impactors (Model 226 and 228), the Andersen, and the two Flow Sensors (Mark 3 and Mark 5) have the disadvantage that adhesives or greases cannot be easily used on the collection substrates to prevent bounce problems. Only the Belfort (MRI), Pollution Control (Pilat), and Brink impactors are designed to be easily used with greases or adhesives. The Flow Sensor Mark 3 differs from the Mark 4 only in having a built-in straight line type preseparator. It is intended to be used with goose neck nozzles. Goose neck nozzles can have very high particle losses down to sizes of 5 μm or smaller and should be avoided. The preferred method of turning the sample stream at the sampler inlet is to use a right angle precollector. Such a precollector can be used as a front end to almost any impactor. The Sierra Model 228 is a Model 226 with additional stages and the Pollution Control Mark 5 is of the same design as the Mark 3 but with more stages. Consequently, we shall only consider one of each pair. We thus have only five impactors left to consider: Andersen Mark III, Sierra Model 228, Flow Sensor Mark 4, Belfort 1502 (MRI), and Pollution Control Mark 5. For convenience, the characteristics of these impactors are summarized in Table 2-3. These possible candidates were scored as shown in Table 2-4 to arrive at the final selections.

Of the six impactors in Table 2-4, the Pollution Control Mark 5 has the advantage of offering 13 jet plates. These multiple plates allow the user to configure the impactor for use in a low loading (clean outlet) situation where a high flow rate is needed or for use in a high loading (inlet) situation where a low flow rate is needed. With the aid of spacers, the operator can use from

Table 2-3. Summary Characteristics of Commercial Instruments

Key No.	Manufacturer	Vender/Model No.	$ Quote X1000	DESCRIPTION/Comments	Key Parameters
GEN	EPA/SoRI design	Right Angle Pre.Co	1.6	Right Angle Impactor Precollector	1 Fr(11 at 0.5 SCFM), several grams
0310	Andersen Samp DAG	Mark III Impactor	4.2	Multi Jet Cascade Impactor,Iso. Stk Smp	9 Fr(F,.4 →10)
4120	Sierra Inst. DAG	Model 228	3.8	Multi Jet Cascade Impactor,Iso. Stk Smp	9 Fr(F,.3 →18)
1720	Flow Sensor DAG	Mark 4	5.8	Multi Jet Cascade Impactor,Iso. Stk Smp	8 Fr(F,.5 → 7)
2910	Belfort	Belfort 1502 (MRI)	2.1	Multi Jet Cascade Impactor,Iso. Stk Smp	8 Fr(F,.5 → 9)
3820	Pollution Control	Mark 5	3.9	Multi Jet Cascade Impactor,Iso. Stk Smp	12 Fr(F,.2 →20)
4910	Zoltec	Brink Model C	2.9	Low Flow M. Jet Cas. Imp., Iso. Stk Smp	8 Fr(F,.5 → 9)
GEN	EPA/SoRI design	6-Stage Cyclone	7.6	Cyclone Set w/SoRI 1,2,3,4,5,F	6 Fr(F,.3 →10),10 gm/stg. SoRI design

Key No.	Comments
GEN	Designed for Loadings > 1 gr/SCF, Right Angle, SoRI/EPA design.
0310	0.5 SCFM (F,.42, .78, 1.2, 2.2, 4.3, 5.9, 9.3, 9.9)Ref 18
4120	0.25SCFM (F, .3, .5, .9, 1.7, 2.7, 4.4, 11, 18)Mfg. Data
1720	0.5 SCFM (F,.52, .90, 1.3, 2.2, 3.0, 4.3, 6.8,)Ref 18, same as Mark 3, Right angle Preseparator, not built in Presep
2910	0.5 SCFM (F,.52, .69, 1.1, 2.2, 4.8, 9.0, 9.0,)Ref 18, sts 1&2 cut at 9 Metrology Res.Inc. was bought by Belfort
3820	0.5 SCFM (F,.21, .28, .36, .46, .62, .80, 1.05, 2.8, 5.6, 14)Mfg.,U of W, Stages interchangable with Mark 3
4910	.03 SCFM (F,.47, .78, 1.1, 2.3, 3.7, 5.4, 9.2)Ref 18, Low Flow for Inlets, High Loading collection stages available
GEN	1.0 ACFM (F,.40, .90, 2.0, 3.2, 8.3) Uses EPA/SoRI 5-Series Cyclone design

		Size Resolution						Concentration Information				Sampling Rate		Nominal	Nozzle Sizes(in.)		Min Port	Max Oper.	
		# of		FINE	MED	COARSE	Dia.	Mass Basis (mg/M3)		Number Basis (#/cm3)		(SCFM)		Flow Rate	Available		Req.	Temp.	Weight
Key No.	Manufacturer	Size Cuts	UF 0→.3	.3→3	3→10	>10	Basis A,P,O	min.	MAX.	min.	MAX.	min.	MAX.	(SCFM)	min	MAX	(in.)	Deg F	(lb)
GEN	EPA/SoRI R. Angle Pre	1	0	0	0	1	A	N/A	High	N/A	N/A	.1	1.2	.5	3/16	1/2	4	820	1
0310	Andersen Samp DAG	8	0	4	3	1	A	N/A	DNA	N/A	N/A	.1	.75	.5	1/8	1/2	3	820	~10
4120	Sierra Inst DAG	8	0	5	1	2	A	N/A	DNA	N/A	N/A	.04	.35	.25	3/32	1/2	3	820	4.5
1720	Flow Sensor DAG	7	0	5	2	0	A	N/A	DNA	N/A	N/A	.1	.75	.5	1/8	1/2	3	850	5
2910	Belfort (MRI)	7	0	4	3	0	A	N/A	DNA	N/A	N/A	DNA	1.0	.5	1/8	1/2	3	450	3.5
3820	Pollution Control	11(13)	2	8	2	1	A	N/A	DNA	N/A	N/A	.02	1.0	.5	3/16	1/2	3	450	15
4910	Zoltec	8	0	4	3	0	A	N/A	DNA	N/A	N/A	.02	.05	.03	3/32	1/2	3	820	7
GEN	EPA/SoRI Des.5-Cyc.	5	0	3	2	0	A	N/A	High	N/A	N/A	.2	1.25	1.0	1/8	1/2	4	820	10

Table 2-4 Point Scoring for Candidate Instruments. (Page 1 of 6)

Max. Value	Performance Criteria	High Loading Inlet Environment[3]							
	Manufacturer: Model No.:	EPA/SoRI Designed[1] Five-Series Cyclone Set	EPA/SoRI Designed[2] Right Angle Precollector	Andersen Mark III Impactor	Sierra Model 228 Impactor	Flow Sensor Mark 4 Impactor	Belfort (MRI) Model 1502 Impactor	Pollution Control (U of W) Mark 5 Impactor	Zoltec Brink Model C Impactor
	I. General Specifications								
E	A. Diameter Bases: Aerodynamic or Stokes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	B. Data Output:								
E	1. Measure of total particulate loading	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E	2. Measure of cumulative mass smaller than specified size	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5%	3. Actual cuts within 10% of specified size	5	5	5	5	5	5	5	5
5%	4. 95% confidence limits	5	5	5	5	5	5	5	5
	C. Sampling Environment								
35%	1. Concentration limits: up to 50 gr/ft^3	35	35	9	18	9	18	26	32
E	2. Stack pressure: -5 to +20 in. H_2O Guage	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
10%	3. Stack temperature: 32 to 840°F	10	10	10	10	10	10	10	10
20%	4. Stack velocity: 10 to 100 ft/sec	20	20	10	10	10	10	15	5
	D. Hardware Features								
10%	1. Component weight limit: 50 lb	10	10	10	10	10	10	10	10
5%	2. Corrosion resistance: acids and alkalies	5	5	5	5	5	5	5	5
E	3. Port requirement: 4 inch	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E	4. Traversing capability	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5%	5. Electrical power: no more than 1650 watts	5	5	5	5	5	5	5	5
5%	6. Length restriction (probe excluded): 6 ft. max.	2	5	5	5	5	5	5	2
	Meets All Essential (E) Criteria (Yes/No):	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Weight Factor*:	97%	100%	64%	73%	64%	73%	86%	79%

*This is the percentage to be applied to the following point values:

Source PM_{10} Method: General Specifications (II F)	- 40 points
Size Distribution Method: General Specifications (III C)	- 20 points
Sized Chemical Sample Method: General Specifications (IV E)	- 25 points
Plume Condensibles Method: General Specifications (VI D)	- 50 points

Table 2-4 (Continued).

Max. Point Value	Performance Criteria (Manufacturer: Model No.:)	High Loading Inlet Environment[3] EPA/SoRI Designed[1] Five-Series Cyclone Set	EPA/SoRI Designed[2] Right Angle Precollector	Andersen Mark III Impactor	Sierra Model 228 Impactor	Flow Sensor Mark 4 Impactor	Belfort (MRI) Model 1502 Impactor	Pollution Control (U of W) Mark 5 Impactor	Zoltec Brink Model C Impactor
	II. Source PM_{10} Method (100 pt.)								
E	A. Aerodynamic Diameter Basis	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
20	B. Operator Skill Level: same as CARB Method 5	20	20	5	5	5	5	5	5
E	C. Cut at 10 μm: 50% collection efficiency at 10 μm aerodynamic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E	D. Sharpness of Cut: $\sigma_g \leq 1.7$	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
20	E. Deviation from CARB Method 5: Only as necessary to obtain the 10 μm size cutoff	15	15	5	5	5	5	5	5
40	F. All of the General Specification Except as Noted Above	39	40	26	29	26	29	34	32
20	G. Potential Interest in a Second Cut at 2.5 μm	15	0	10	10	10	10	10	10
	Meets All Essential (E) Criteria (Yes/No):	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Total Point Score:	89	75	46	49	46	49	54	52
	III. Size Distribution Method (100 pt.)								
	A. Size Range								
E	1. Cumulative mass < 0.2 μm	Yes		Yes	Yes	Yes	Yes	Yes	Yes
30	2. Range of interest: 0.2 μm→10 μm	25	No	5	15	5	5	20	20
30	3. Size resolution: 5 to 8 cuts within 0.2→10 μm range, evenly spaced logD (constant ratio), maximum ratio 2.15, minimum ratio 1.63	20	No	15	20	15	20	25	20
5	4. Sharpness of cut: $\sigma_g \leq 1.5$	5		5	5	5	5	5	5
5	5. Calibrations identified as to configuration: grease, glass fiber, quartz fiber, bare metal, etc.	5		5	5	5	5	5	5
10	B. Measure of Total Particulate Loading	10		10	10	10	10	10	10
20	C. All the General Specifications Except as Specified Above	19		13	15	13	15	17	16
	Meets All Essential (E) Criteria (Yes/No):	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
	Total Point Score:	84		53	70	53	60	82	76

Table 2-4 (Continued).

Max. Point Value	Performance Criteria	Manufacturer: Model No.:	High Loading Inlet Environment[3] EPA/SoRI Designed[1] Five-Series Cyclone Set	EPA/SoRI Designed[2] Right Angle Precollector	Andersen Mark III Impactor	Sierra Model 228 Impactor	Flow Sensor Mark 4 Impactor	Belfort (MRI) Model 1502 Impactor	Pollution Control (U of W) Mark 5 Impactor	Zoltec Brink Model C Impactor
	IV. Sized Chemical Sample Method (100 pt.)									
30	A. Size Fractions, Aerodynamic Diameter 1. d < .25 μm 2. .25 - 1 μm 3. 1 - 2.5 μm 4. 2.5 - 10 μm 5. >10 μm		25	No						
5	B. Sharpness of Cut: $\sigma_g \leq 1.7$		5							
40	C. Bulk Sample Quantities: 10-100 mg for each size fraction		40		No	No	No	No	No	No
E	D. Sample Contamination: Unaltered, contamination free samples		Yes		No	No	No	No	No	No
25	E. All the General Specifications Except as Specified Above		25							
		Meets All Essential (E) Criteria (Yes/No):	Yes	No	No	No	No	No	No	No
		Total Point Score:	95							

[1]There are two manufacturers of the EPA/SoRI designed Five-Series Cyclone Set, Andersen Group, and InTox. With respect to performance these cyclone sets are equivalent because their internal dimensions are taken from the EPA/SoRI design. Externally they differ slightly with respect to the techniques used to connect and disconnect the various cyclones.

[2]There are two manufacturers of the EPA/SoRI designed Right Angle Precollector, Andersen Group, and Pollution Control. Both have the same performance characteristics but differ slightly externally. The right angle precollector is an accessory to the cascade impactor and may be connected to any of the impactors listed except the Zoltec Brink Model C. A special cyclone is integral with the Brink that serves as a right angle precollector. The evaluations assume that a right angle precollector will be used together with the respective impactor.

[3]Most impactors are designed to operate in a low loading outlet environment and use high flow rates (1 acfm) to keep the sampling times to a minimum. When the same impactor is used in a high loading inlet environment where the concentrations may be 10^4 higher, problems of stage overloading and short run times are encountered. The Five-Series Cyclones can hold tens of grams per stage without overloading and may thus be operated at high flow rates at the inlet.

Table 2-4 (Continued).

Max. Value	Performance Criteria	Manufacturer: Model No.:	EPA/SoRI Designed[1] Five-Series Cyclone Set	EPA/SoRI Designed[2] Right Angle Precollector	Andersen Mark III Impactor	Sierra Model 228 Impactor	Flow Sensor Mark 4 Impactor	Belfort (MRI) Model 1502 Impactor	Pollution Control (U of W) Mark 5 Impactor	Zoltec Brink Model C Impactor
			Low Loading Outlet Environment[3]							
	I. General Specifications									
E	A. Diameter Bases: Aerodynamic or Stokes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	B. Data Output:									
E	1. Measure of total particulate loading		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E	2. Measure of cumulative mass smaller than specified size		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5%	3. Actual cuts within 10% of specified size		5	5	5	5	5	5	5	5
5%	4. 95% confidence limits		5	5	5	5	5	5	5	5
	C. Sampling Environment									
35%	1. Concentration limits: down to 0.005 gr/ft^3		18	35	35	26	35	35	35	4
E	2. Stack pressure: -5 to +20 in. H_2O Guage		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
10%	3. Stack temperature: 32 to 840°F		10	10	10	10	10	10	10	10
20%	4. Stack velocity: 10 to 100 ft/sec		20	20	10	15	10	15	20	8
	D. Hardware Features									
10%	1. Component weight limit: 50 lb		10	10	10	10	10	10	10	10
5%	2. Corrosion resistance: acids and alkalies		5	5	5	5	5	5	5	5
E	3. Port requirement: 4 inch		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E	4. Traversing capability		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5%	5. Electrical power: no more than 1650 watts		5	5	5	5	5	5	5	5
5%	6. Length restriction (probe excluded): 6 ft. max.		2	5	5	5	5	5	5	2
	Meets All Essential (E) Criteria (Yes/No):		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Weight Factor*:		80%	100%	90%	86%	90%	95%	100%	54%

*This is the percentage to be applied to the following point values:

Source PM_{10} Method: General Specifications (II F)	- 40 points
Size Distribution Method: General Specifications (III C)	- 20 points
Sized Chemical Sample Method: General Specifications (IV E)	- 25 points
Plume Condensibles Method: General Specifications (VI D)	- 50 points

Table 2-4 (Continued).

Max. Point Value	Performance Criteria	Manufacturer: Model No.:	EPA/SoRI Designed[1] Five-Series Cyclone Set	EPA/SoRI Designed[2] Right Angle Precollector	Andersen Mark III Impactor	Sierra Model 228 Impactor	Flow Sensor Mark 4 Impactor	Belfort (MRI) Model 1502 Impactor	Pollution Control (U of W) Mark 5 Impactor	Zoltec Brink Model C Impactor
			Low Loading Outlet Environment[3]							
	II. Source PM_{10} Method (100 pt.)									
E	A. Aerodynamic Diameter Basis		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
20	B. Operator Skill Level: same as CARB Method 5		20	20	5	5	5	5	5	5
E	C. Cut at 10 µm: 50% collection efficiency at 10 µm aerodynamic		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E	D. Sharpness of Cut: $\sigma_g \leq 1.7$		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
20	E. Deviation from CARB Method 5: Only as necessary to obtain the 10 µm size cutoff		15	15	5	5	5	5	5	5
40	F. All of the General Specification Except as Noted Above		32	40	36	34	36	38	40	22
20	G. Potential Interest in a Second Cut at 2.5 µm		15	0	10	10	10	10	10	10
	Meets All Essential (E) Criteria (Yes/No):		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Total Point Score:		82	75	56	54	56	58	60	42
	III. Size Distribution Method (100 pt.)									
	A. Size Range									
E	1. Cumulative mass < 0.2 µm		Yes		Yes	Yes	Yes	Yes	Yes	Yes
30	2. Range of interest: 0.2 µm→10 µm		25	No	22	25	22	22	28	20
30	3. Size resolution: 5 to 8 cuts within 0.2→10 µm range, evenly spaced logD (constant ratio), maximum ratio 2.15, minimum ratio 1.63		20	No	25	25	25	25	28	20
5	4. Sharpness of cut: $\sigma_g \leq 1.5$		5		5	5	5	5	5	5
5	5. Calibrations identified as to configuration: grease, glass fiber, quartz fiber, bare metal, etc.		5		5	5	5	5	5	5
10	B. Measure of Total Particulate Loading		10		10	10	10	10	10	10
20	C. All the General Specifications Except as Specified Above		16		18	17	18	19	20	11
	Meets All Essential (E) Criteria (Yes/No):		Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
	Total Point Score:		81		85	87	85	86	96	71

Table 2-4 (Continued).

Max. Point Value	Performance Criteria	Manufacturer: Model No.:	Low Loading Outlet Environment[3] EPA/SoRI Designed[1] Five-Series Cyclone Set	EPA/SoRI Designed[2] Right Angle Precollector	Andersen Mark III Impactor	Sierra Model 228 Impactor	Flow Sensor Mark 4 Impactor	Belfort (MRI) Model 1502 Impactor	Pollution Control (U of W) Mark 5 Impactor	Zoltec Brink Model C Impactor
	IV. Sized Chemical Sample Method (100 pt.)									
30	A. Size Fractions, Aerodynamic Diameter 1. d < .25 μm 2. .25 - 1 μm 3. 1 - 2.5 μm 4. 2.5 - 10 μm 5. >10 μm		25	No						
5	B. Sharpness of Cut: σ_g < 1.7		5							
40	C. Bulk Sample Quantities: 10-100 mg for each size fraction		40		No	No	No	No	No	No
E	D. Sample Contamination: Unaltered, contamination free samples		Yes		No	No	No	No	No	No
25	E. All the General Specifications Except as Specified Above		25							
		Meets All Essential (E) Criteria (Yes/No):	Yes	No	No	No	No	No	No	No
		Total Point Score:	95							

[1]There are two manufacturers of the EPA/SoRI designed Five-Series Cyclone Set, Andersen Group, and InTox. With respect to performance these cyclone sets are equivalent because their internal dimensions are taken from the EPA/SoRI design. Externally they differ slightly with respect to the techniques used to connect and disconnect the various cyclones.

[2]There are two manufacturers of the EPA/SoRI designed Right Angle Precollector, Andersen Group, and Pollution Control. Both have the same performance characteristics but differ slightly externally. The right angle precollector is an accessory to the cascade impactor and may be connected to any of the impactors listed except the Zoltec Brink Model C. A special cyclone is integral with the Brink that serves as a right angle precollector. The evaluations assume that a right angle precollector will be used together with the respective impactor.

[3]Most impactors are designed to operate in a low loading outlet environment and use high flow rates (1 acfm) to keep the sampling times to a minimum. When the same impactor is used in a high loading inlet environment where the concentrations may be 10^4 higher, problems of stage overloading and short run times are encountered. The Five-Series Cyclones can hold tens of grams per stage without overloading and may thus be operated at high flow rates at the inlet.

one to eleven stages at a time. A common practice is to use a Mark 3 shell and pick the six or seven stages (from the 13) that give the desired cuts at a suitable flow rate. This capability of custom picking the jet plates to be used is a great asset. The bore of the inlet tube serves as the first jet. This frequently has a D_{50} close to that of the precollector and tends to catch any particles which should have been caught by, but have bounced past, the precollector. This helps alleviate two of the major problems encountered in the use of cascade impactors - particle bounce and overloading in the upper stages. This impactor is also the only one of the five which can provide size cuts smaller than 0.3μm. It is for these reasons that we recommend the Pollution Control Mark 5 Cascade Impactor and right angle precollector as the instrumentation to be used by CARB for the Size Distribution Method.

Note: The discussion in Section 2.5.2 on anisokinetic sampling problems also applies to the Size Distribution Method.

2.5.4 Sized Chemical Sample Method

Cascade cyclones are preferred as the instrumentation for the Sized Chemical Sample Method. HCSS (High Concentration Source Sampling) Impactors may serve as an alternative option. The impactors combine two impaction chambers, a cyclone and a filter. Manufacturer's data for the Andersen HCSS impactors show D_{50}'s of 10.8 μm, 5.8 μm, and 1.5 μm for 0.5 acfm at 70°F. The Five-Series Cyclone set has cuts of 0.55, 1.3, 1.8, 3.6, and 7.2 μm when operated at 1.0 acfm at a temperature of 300°F. These come closer to the specifications given in Section 2.2.4. By operating the sampler at higher flow rates and adding another cyclone having a coarser cut, it is expected that cuts near those in the specifications can be obtained. The series cyclone set was originally designed for the purpose of collecting size segregated samples for chemical analysis and clean, unaltered bulk samples in excess of 100mg are readily obtainable with it. As discussed previously, two companies supply the EPA/SoRI design Five-Series Cyclone; Andersen (Flow Sensor Division) and InTox. Metal O-rings are available for high temperature operation. Summary information on the cyclones is provided in Table 2-4.

2.5.5 Plume Condensibles Method

No commercial hardware exists which meets the performance criteria for this method. Prototype equipment, however, does exist which meets the criteria. This instrumentation was developed by SoRI under contract to EPA and is described in Section 4, "The Stack Dilution Sampling System" (p. 159-170) of EPA 600/7-82-036, May 1982, Sampling and Data Handling Methods for Inhalable Particulate Sampling, Wallace B. Smith. The simulator can serve as a sample extraction/dilution system for ambient particle sizing instrumentation such as a filter for mass measurements, a commercial Hi-Vol impactor, and various other instruments designed for Ambient Airborne Aerosols (TSI APS 33, QCM Impactors, etc.). The Stack Dilution Sampling System (SDSS) incorporates an in situ cyclone that operates with a D_{50} of 2.5 μm.

2.5.6 Five Year Costing

Table 2-5 shows five-year life cycle costs for the Size Distribution Method using cascade impactors, Sized Chemical Sample Method using series cyclones, and Stationary Source PM_{10} Method using the PM_{10} cyclone (Cyclone I of the EPA/SoRI cyclone set). For comparison purposes costs developed on the same basis are also shown for CARB Method 5. The equipment cost shown for the sampler is an approximate cost, the true cost would depend on which make/model is purchased. The assumptions used are shown in the table, and may need to be adjusted if the labor rates, etc. used were not close to the true values. As one can see, the major cost is in labor, consequently if a particular sampler design is simple to operate, the resultant labor cost savings can be quite substantial.

Table 2-5. Five-Year Life Cycle Costing Details (Page 1 of 2)

Description of Cost Item	Cascade Impactors	5-Series Cyclones	PM-10 Cyclone	Method 5	Details (Typical Vendor/Model)
I. Capital Costs					
A. Equipment Sampler with Accessories					
1. Sampler (Includes Filter)	2x4,000	7,600	2,000	000	Specific to Sampler Type
2. Right Angle Pre-Collector with Nozzles	$ 2x1,300	N/A	N/A	N/A	Flow Sensor DAG
3. Filter Holder, 63 mm (Blank Runs)	$ 600	N/A	N/A	N/A	Andersen DAG No. P-3901-63
B. Necessary Support Equipment Peculiar to the Sampling Technique Used					
1. Pre/Post Test					
a. Laboratory Oven	$ 750	N/A	N/A	N/A	Blue M Co. Model OV-18A Bench Type, Gravity Convection
b. Wet Test Meter (.1 ft^3)	$ 2,500	$ 2,500	$ 2,500	$ 2,500	Sargent Welch S-39446
2. On Site Equipment					
a. Method 5 Sampling Train (Probe, Pitot, Umbilical, sample case with glassware, control unit with detachable pump housing)	$ 2x7,000	$ 7,000	$ 7,000	$ 7,000	Nutech Model 2010-100
b. Low Flow Orifices	$ 2x200	N/A	N/A	N/A	Custom Shopwork. M5=0.180" I.D., ΔH@=1.84. Medium=0.130" I.D., ΔH@=5.0. Low=0.093" I.D., ΔH@=18.
c. Field Flow Audit Orifice (Quality Control Audit)	$ 100	$ 100	$ 100	$ 100	Custom Shopwork. Critical Orifice. Operate at 19 "Hg Negative, 0.059" I.D.
d. Triple Beam Balance (1/10 g, + 2000 g)	$ 160	$ 160	$ 160	$ 160	Ohaus Dial-O-Gram Model 1650W
e. Analytical Balance (1/10 mg)	N/A	$ 2,900	$ 2,900	$ 2,900	Mettler Model AE 163
f. Analytical Balance (1/100 mg)	$ 7,700	N/A	N/A	N/A	Cahn Model 27 Automatic Microbalance
C. General Support Equipment					
1. Data Analysis/Run Parameter Calculation	$ 2,200	$ 2,200	$ 2,200	N/A	Apple IIe System (128K RAM, Monitor, 2 Disk Drives, Graphics capable printer)
2. Special Tools (Port Cleaning)	$ 350	$ 350	$ 350	N/A	Portable Horizontal Wheel Grinder. Black & Decker No. 4266 (2 1/2" wheel, 19,000 RPM)
3. Support Equipment					
a. Flue Gas Analyzer	$ 550	$ 550	$ 550	$ 550	Orsat Flue Gas Analyzer (O_2, CO_2, CO). Sargent Welch S-38070
b. Shipping Container	$ 200	$ 200	$ 200	$ 200	Polyethylene Shipping Container, Hardigg Industries, Inc. No. AL3620-1704 (Inner L-W-H: 36-20-21; 12 ft^3)
TOTAL CAPITAL COST:	$ 40,110	$ 23,560	$ 17,960	$ 13,410	

Table 2-5. Five-Year Life Cycle Costing Details (Page 2 of 2)

Description of Cost Item	Cascade Impactors		Series Cyclones		PM-10 Cyclone		Method 5 Mass Train	
II. Training Cost								
A. Training Seminar (Tuition, Travel, Manhours: $600 + $400RT + 5x ($85 + $65) + 48H	$ 3,405	--	$ 3,405	--	$ 3,405	--	$ 3,405	--
B. Study Time-Manuals	$ 280	8H	$ 208	8H	$ 280	8H	$ 280	8H
C. On the Job Training (Observer/Trainee)	$ 1,400	40H	$ 1,400	40H	$ 1,400	40H	$ 1,400	40H
	$ 5,085		$ 5,085		$ 5,085		$ 5,085	
III. Operating Cost								
A. Assumed Number of Field Tests - Five Year Period	(50)	5x10	(50)	5x10	(50)	5x10	(50)	5x10
B. Unit Costs for One Field Test								
1. Assumptions:								
a. Minimum Number of Sampling Runs Required	--	7	--	1	--	3	--	3
b. Run Time (0)	--	2H	--	40H	--	2H	--	2H
c. Required Samplers Available (Minimizes Turn Around/Warmup Time)	--	2	--	1	--	1	--	1
d. Travel Destinations drive time, no airfare	--	2H	--	2H	--	2H	--	2H
e. Pre-Site Inspection Expenses (12 hr., 1 day car, 1 day Subsistance)	$ 565	--	$ 565	--	$ 565	--	$ 565	--
f. Site Preparation Expenses (Sample Platforms, Power, etc.)	$ 400	--	$ 400	--	$ 400	--	$ 400	--
g. Crew Size for one system (3 or 4 people)	--	2	--	2	--	2	--	2
h. $Rates: $35/Manhour; $60/day rental vehicle $85/day/person subsistance; 8 hour days (d)	--	--	--	--	--	--	--	--
2. Pre-test Preparations								
a. Substrate Conditioning	$ 140	4H	--	N/A	--	N/A	--	N/A
b. Substrate Weighings	$ 140	4H	$ 70	2H	$ 70	2H	$ 70	2H
c. Lab Calibrations	$ 140	4H	$ 140	4H	$ 140	4H	$ 140	4H
d. Equipment Preparation	$ 280	8H	$ 280	8H	$ 280	8H	$ 280	8H
3. On-Site Cost								
a. Travel Expenses								
(1) Rental Vehicles ($)	$ 300	5d	$ 180	3d	$ 180	3d	$ 180	3d
(2) Subsistance ($)	$ 680	2x4d	$ 340	2x2d	$ 340	2x2d	$ 340	2x2d
b. Travel, Sampling and Lab Manhour	$ 2,800	2x4d	$ 1,750	2x2.5d	$ 1,400	2x2d	$ 1,400	2x2d
c. Expendables (Filters, substrates, etc.)	$ 400	--	$ 200	--	$ 200	--	$ 200	--
4. Post Test Cost								
a. Equipment Restoration	$ 280	8H	$ 280	8H	$ 280	8H	$ 280	8H
b. Post Test Calibrations	$ 140	4H	$ 140	4H	$ 140	4H	$ 140	4H
5. Data Analysis and Reporting	$ 840	24H	$ 560	16H	$ 560	16H	$ 560	16H
TOTAL UNIT COST One Field Test	$ 6,140		$ 3,940		$ 3,590		$ 3,590	
C. Total Operating Costs for Five Years	$ 307,000		$ 197,000		$ 179,500		$ 179,500	
IV. Total Cost: Five Year Life Cycle (Capital Costs + Training + Operating 50 Tests)	$ 347,110		$ 220,560		$ 197,460		$ 192,910	

SECTION 3

PROPOSED PARTICLE SIZE DISTRIBUTION MEASUREMENT METHOD

3.1 Introduction

Moderate to high resolution particle size distribution information is needed for research applications and for control device selection and permitting in that this information provides a basis for estimating expected efficiencies of control devices. Experience has shown that for most applications the critical range over which size distribution data is needed is from about 0.2 μm to 10 μm, together with total concentrations for the ranges smaller than 0.2 μm and larger than 10 μm. Sufficient resolution for modeling the effects of control devices, estimating overall control device efficiencies, predicting stack opacities (for noncondensing stacks), and characterizing the fractional collection efficiencies of operating control devices can be provided by separating the aerosol particles into about six to eight size classes within the 0.2 μm to 10 μm size range. The range also includes "respirable" particles and consequently is of special importance in health effects.

After reviewing all available methods for measuring particle size distributions, the method of inertial separation using cascade inertial impactors was selected as the preferred technique (standard method) for measuring particle size distributions of effluents from stationary sources. This method, of all those available, most nearly met all of the specifications set forth above.

For years inertial impactors have been commonly used to determine the particle size distribution of particulate matter suspended in industrial process gases, especially those emitted to the atmosphere. Impactors have several advantages over competing equipment: they are compact, they can be inserted directly into gas ducts (avoiding the problems associated with extractive sampling), they are fairly accurate, and they produce information which has been widely used and understood. The majority of the particle-size distribution data available on industrial process streams have been taken using cascade impactors covering a diameter range of 0.3 to 20 μm. These devices consist of serial configurations of several impaction stages. Each stage of the impactor removes particles over a limited range of diameters, starting with the largest and progressing to smaller diameters. The popularity of these devices is due not only to their simplicity of design and operation but also to their portability and adaptability to a large variety of aerosol streams.

When used properly, cascade impactors are capable of providing particle size distribution measurements extending from below 0.5 μm to diameters of 10 μm and above.

3.2 Basic Principles of Cascade Impactor Performance

Figure 3-1 is a schematic diagram illustrating the principles of particle collection common to all inertial impactors. The sample aerosol is constrained to pass through a circular hole or rectangular slit to form a jet that is directed toward an impaction surface. Large particles will possess sufficient

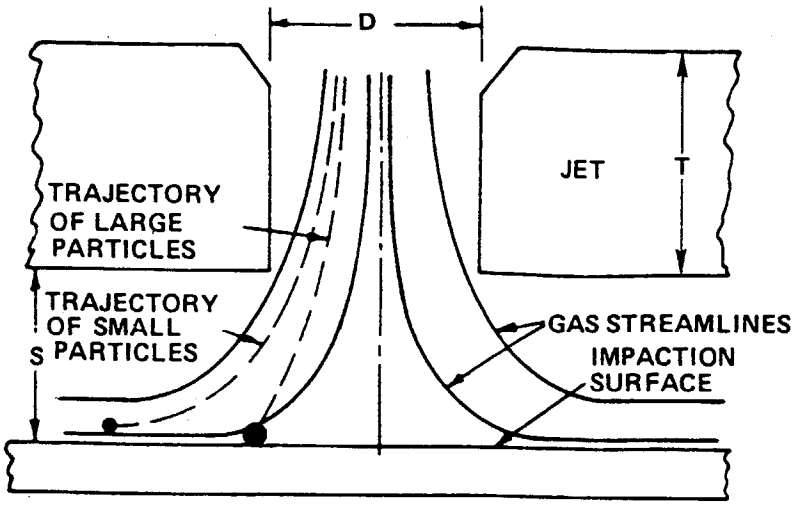


Figure 3-1. Typical impactor jet and collection plate.

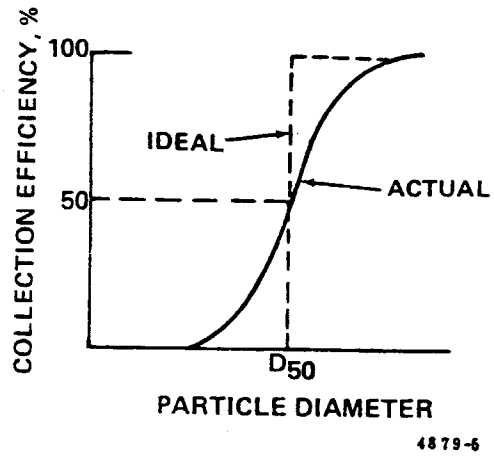


Figure 3-2. Generalized stage collection efficiency curve for a cascade impactor.

inertia to cross the gas streamlines and impact on the collection surface. Particles having lower momenta will follow the gas stream past the collection plate. In a cascade impactor the gas stream passes sequentially through several impaction stages designed to remove successively smaller particles, thus collecting the airborne particulate matter in a series of discrete size fractions.

The probability of collection in an impactor stage typically varies with particle size as shown in Figure 3-2. Ideally, an impaction stage would provide complete collection of all particles larger than a known size and pass all smaller particles. In other words, the ideal collection efficiency curve would be a step function. In practice, the real stage collection efficiency curves such as the one schematically illustrated have sharp enough transitions to be useful for aerosol size distribution measurements. The behavior of a real stage in operation is then described in terms of a characteristic particle diameter which is collected with 50 percent efficiency for the operating conditions used. The latter diameter is called the D_{50} of the stage.

Impactors with a wide variety of geometrical configurations have been observed to have the qualitative behavior described above. Impactor stages have been constructed with one to several hundred holes or rectangular jets, depending on the desired jet velocity and volumetric flow rate. The number of jet stages ranges from one to about 20 for various impactor geometries reported in the literature; most commercially available impactors use 5 to 10 stages.

3.2.1 Scaling Relationships

Parameters which determine the collection efficiency for a given stage geometry are particle density, gas viscosity, gas velocity throughout the jet, jet diameter for circular jets, or jet width and length for rectangular jets, jet-to-plate spacing, and thickness of the jet orifice. Certain dimensionless factors can be defined which allow scaling relationships in stage efficiency to be predicted. Gas flow in the impactor jet can be scaled in the typical manner by using Reynolds number (Re) of the gas referenced to the jet dimension as a dimensionless gas velocity. For circular jets, the relation is

$$Re = \frac{\rho_g V_j D_j}{\mu} \qquad (3\text{-}1)$$

where

ρ_g = gas density (g/cm^3),

V_j = mean jet inlet velocity (cm/s),

D_j = jet diameter (cm),

and μ = gas viscosity (g/cm sec).

Other geometric parameters can likewise be referenced to the jet width. For round jets, the important dimensionless ratios are relative jet to plate spacing (S_j/D_j) and relative jet thickness (T_j/D_j). Where D, T, and S are dimensions as shown in Figure 3-1. These dimensionless ratios and the jet Reynolds number are sufficient to define the gas flow field for a given impactor geometry.

Similar scaling relationships can be developed for particle motion in the impactor. Since particle motion relative to the gas stream is assumed to obey Stokes' law, a dimensionless inertial parameter related to particle size can be defined in terms relating to particle motion in a continuous viscous medium. This inertial size parameter (the impaction parameter), ψ, is defined as

$$\psi = D_p^2 \left(\frac{C\rho_p V_0}{18\mu D_j}\right)$$

where

D_p = Stokes diameter of a spherical particle (cm),

ρ_p = particle density (g/cm^3),

C = Cunningham slip correction factor (dimensionless), defined by Equation 3-3,

V_0 = initial particle velocity in the jet (cm/s).

The remaining quantities are as defined previously.

As defined above, ψ is the ratio of an inertial characteristic length (the stopping distance of a particle injected with initial velocity V_0 into still air) to the diameter of the impactor jet. Alternately, ψ is equal to the ratio of an inertial characteristic time (the particle relaxation time in the fluid) to a transit time characteristic of the system (the ratio of the particle's initial velocity to the jet diameter). Inspection of equation (3-2) reveals that $\sqrt{\psi}$ has the form of a dimensionless particle diameter. Alternate dimensionless inertial constants can also be defined. Another such constant frequently used is the Stokes number (STK), defined as the ratio of the particle stopping distance of a particle injected with initial velocity V_0 into still air to the radius or half-width of the jet, so that STK = 2ψ. In this document we will use STK in many of the discussions but will use ψ as defined by equation (3-2) when reducing data.

The quantities in equation (3-2) which are dependent on the particle enter as the product $C\rho_p D_p^2$, which only has meaning for spherical particles of known density. Since impactors are also used to characterize particles which are not spherical or are of unknown density, it is useful to define certain equivalent

diameters on the basis of aerodynamic behavior of the particles. The three common equivalent diameters used in this text are the Stokes, classical aerodynamic, and aerodynamic impaction diameters. The Stokes diameter of a particle is defined as the diameter of a spherical particle having the same density and the same aerodynamic characteristics (e.g., terminal settling velocity in air) as the particle in question.

In this document, the Stokes equivalent diameter is typically used unless otherwise explicitly stated; in particular, D_p in equation (3-2) is the Stokes diameter. The classical aerodynamic diameter of a particle is the physical diameter of a particle with density of 1.0 g/cm^3 which has the same aerodynamic behavior as the particle in question. This equivalent diameter is useful when the particle density is unknown or irrelevant. The aerodynamic impaction diameter of a particle is defined as the quantity $D_p\sqrt{C\rho_p}$, where D_p is the Stokes diameter. This equivalent diameter (Mercer et al., 1968), has the useful feature that it incorporates the size-dependent correction C. It thus eliminates iterative calculations otherwise required to determine particle diameter from aerodynamic measurements.

The Cunningham factor, C, in equation (3-2) is an empirical correction for the breakdown of the assumption that the fluid medium is a continuum. For particle diameters on the order of the mean free path of molecules in the gas, the net drag force seen by a moving particle is decreased by the ratio 1/C. Within the Stokes model, this behavior can be visualized as a gas medium which is continuous, but which "slips" past the particle surface. This model is reflected in the alternate name "slip correction factor". The numerical value of C is given (Fuchs, 1964) by equation (3-3),

$$C = 1 + \frac{2\ell}{D}\left[1.23 + 0.41 \exp\left(\frac{-0.44D}{\ell}\right)\right] \qquad (3\text{-}3)$$

where

ℓ = mean free path of the gas medium (cm),

D = Stokes diameter of the particle (cm).

Other empirical equations with slightly different constants but having the same form as (3-3) are also found in the literature. Under conditions where the particle diameter is comparable to or smaller than the gas mean free path, the Cunningham correction becomes large enough to be a controlling factor in the aerodynamic behavior of the particle. These conditions are observed in impactors designed to operate at reduced pressure. In these devices, the large Cunningham factors due to the increased gas mean free path allow inertial impaction of particles with diameters less than 0.05 μm, extending the potential range of size distribution measurements by over an order of magnitude. While this effect is mentioned here for completeness, low pressure impactors are beyond the scope of the proposed ARB method. For typical gas conditions and particle diameters above 0.5 μm, the Cunningham correction factor provides a significant but relatively small (<35%) correction to the effective aerodynamic diameter of the particle.

3.2.2 Theory of Impactor Behavior

Although various attempts have been made to predict the behavior of particles in an impactor stage, the most comprehensive theoretical treatment was performed by Marple (Marple, 1970; Marple and Liu, 1974). Marple numerically solved the two-dimensional Navier-Stokes equations for the laminar flow of an incompressible viscous fluid within a single-jet impactor stage. Having obtained the gas flow field for a given gas Reynolds number and stage geometry (defined by S_j/W_j, T_j/W_j, and the choice of round or rectangular jets), numerical integration of the equations of motion of particles in the flow field is possible. Marple generated theoretical impaction efficiency curves by generating trajectories for particles of selected initial conditions and different size (Marple chose to use the square root of the Stokes number, $\sqrt{STK}$, as his dimensionless inertial size parameter).

The variables of the Marple's model are jet throat T relative to the jet diameter W (T/W), jet-to-plate-distance S relative to W (S/W), and Reynolds number, Re. Marple (1970) investigated a range of geometries and Reynolds numbers by varying each of the three parameters while leaving the other two fixed at reference values. For round jet impactors, these reference values were Re = 3000, $S_j/W_j = 1/2$, and $T_j/W_j = 1$. Marple's efficiency curves for this range of parameters are shown in Figure 3-3. As can be seen in the figure, variation of S_j/W_j above about 1/2 and variation of T_j/W_j above about 1/4 did not seem to affect the efficiency curves for the reference Reynolds number of 3000. As seen in Figure 3-4, the $\sqrt{STK_{50}}$ value for the reference geometry was not a strong function of Reynolds number in the range 100 - 1000. Thus, Marple's calculations tended to reinforce the conclusion that a single calibration constant $\sqrt{STK_{50}}$ (or $\sqrt{\psi_{50}}$) could characterize an impactor stage over a broad range of temperature and flow rate.

Recently, calculations using Marple's formalism have been repeated for impactor geometries more typical of commercially available cascade impactors (Farthing, 1983). Specifically, larger values of S_j/W_j (up to 11) were used in these calculations. Trajectories were calculated to obtain stage collection efficiencies. Typical curves are illustrated in Figures 3-5 and 3-6. It is seen that at S/W = 1/2, changes in Re cause small changes in impactor behavior. At larger values of S/W, changes in Re cause substantial changes in $\sqrt{STK_{50}}$ as well as minor changes in the slope of the curves (in log ($\sqrt{STK_{50}}$). As shown in Figure 3-7, $\sqrt{STK_{50}}$ becomes a much stronger function of stage Reynolds number for larger jet-to-plate spacings than at Marple's reference value of $S_j/D_j = .5$. In extreme limits of low Reynolds number and large S_j/D_j, $\sqrt{STK_{50}}$ may be higher than the value predicted from Marple's early calculations by as much as 200% to 300%.

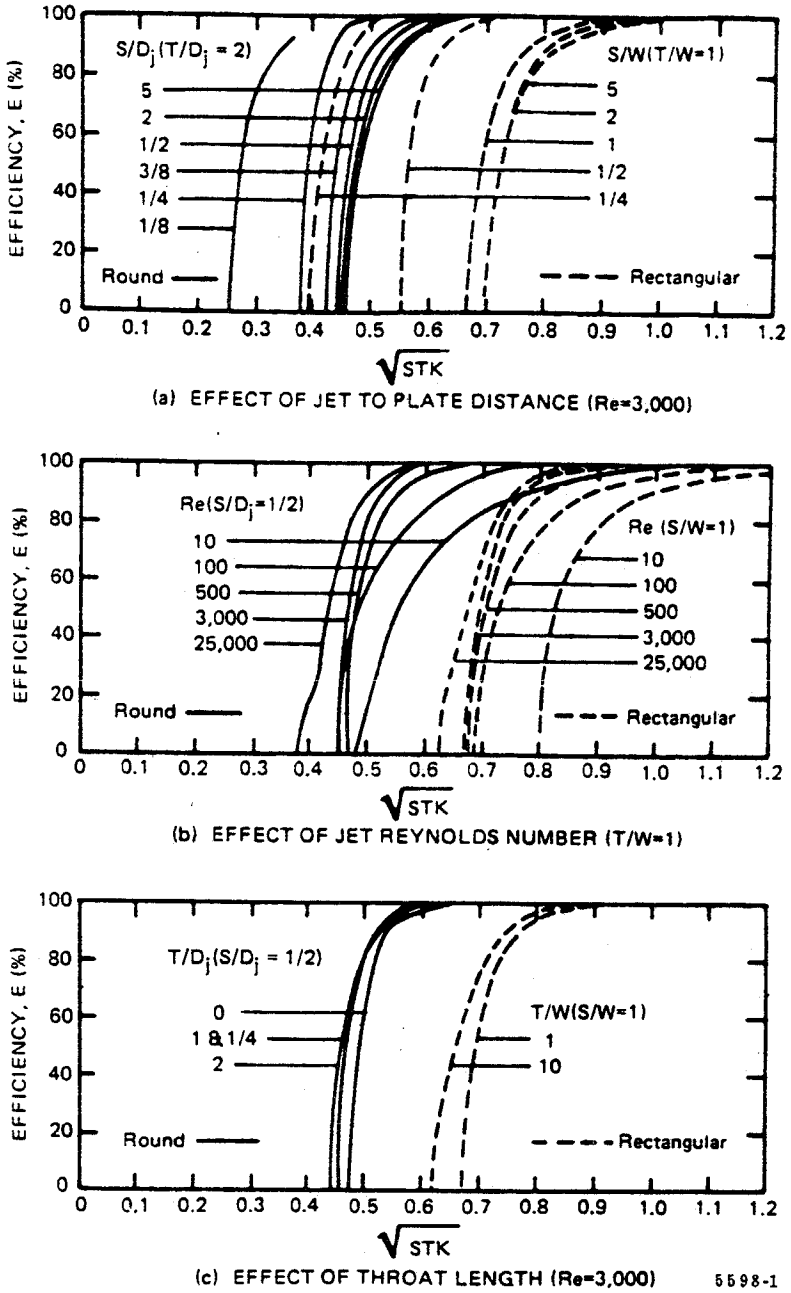


Figure 3-3. Theoretical impactor efficiency curves for rectangular and round jet impactors showing the effect of jet-to-plate distance S, Reynolds number Re, and throat length T (Marple, 1970).

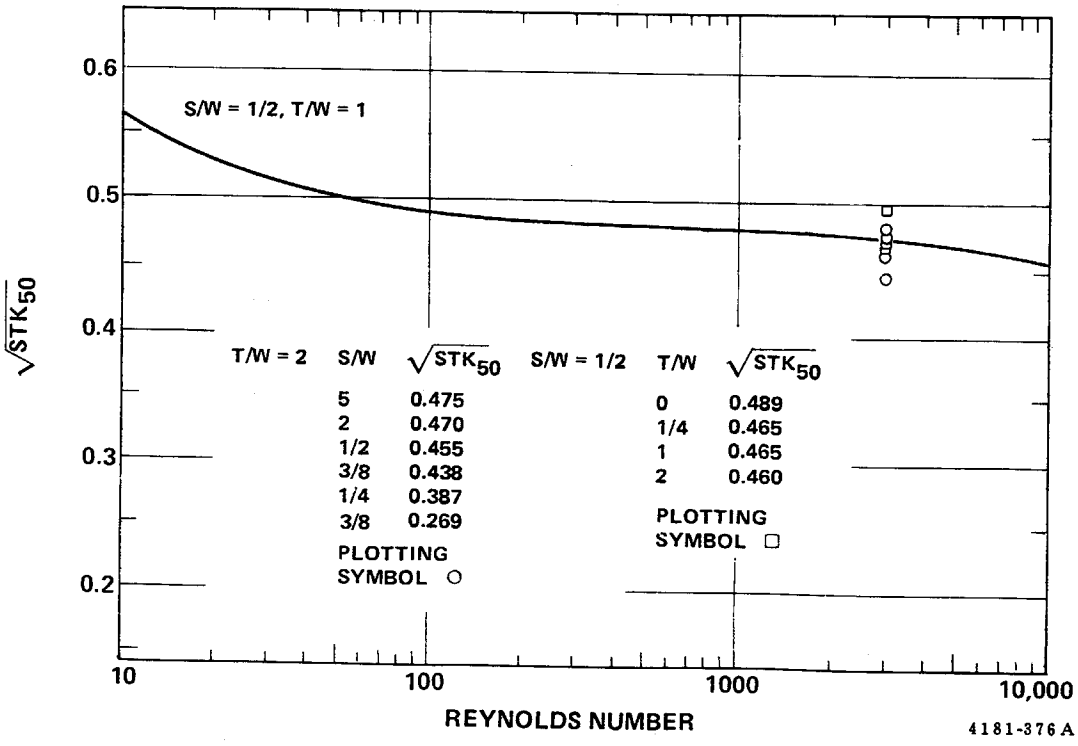


Figure 3-4. Variation of $\sqrt{STK_{50}}$ with Reynold's number from Marple (1970). Points shown are from calculations done at SoRI.

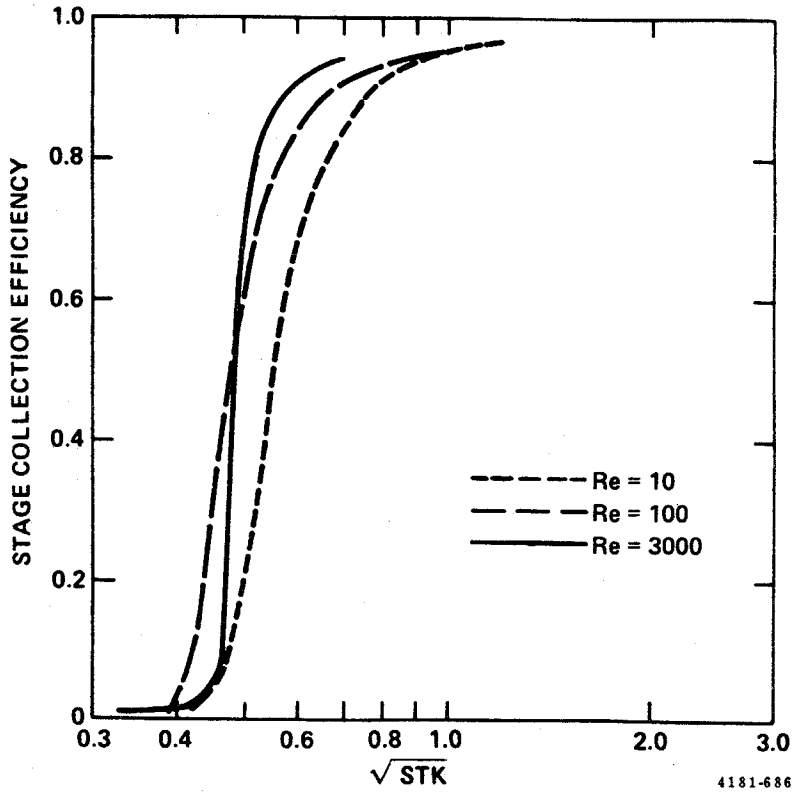


Figure 3-5. Impactor collection efficiency calculated from Marple's Theory. S/W = 1/2 and T/W = 2 (Farthing, 1983).

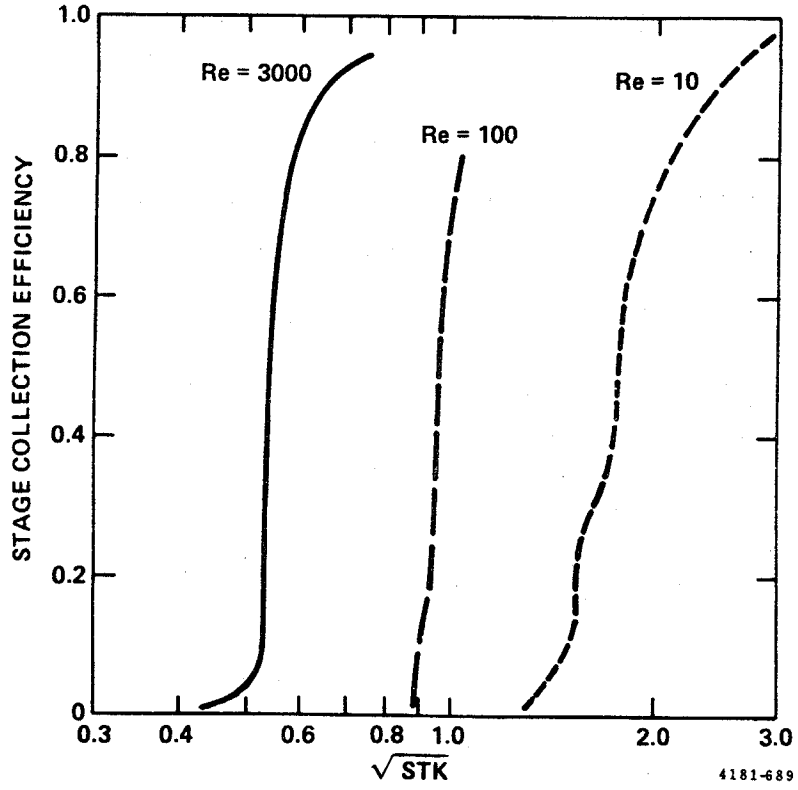


Figure 3-6. Impactor collection efficiency calculated from Marple's Theory. S/W = 11 and T/W = 2 (Farthing, 1983).

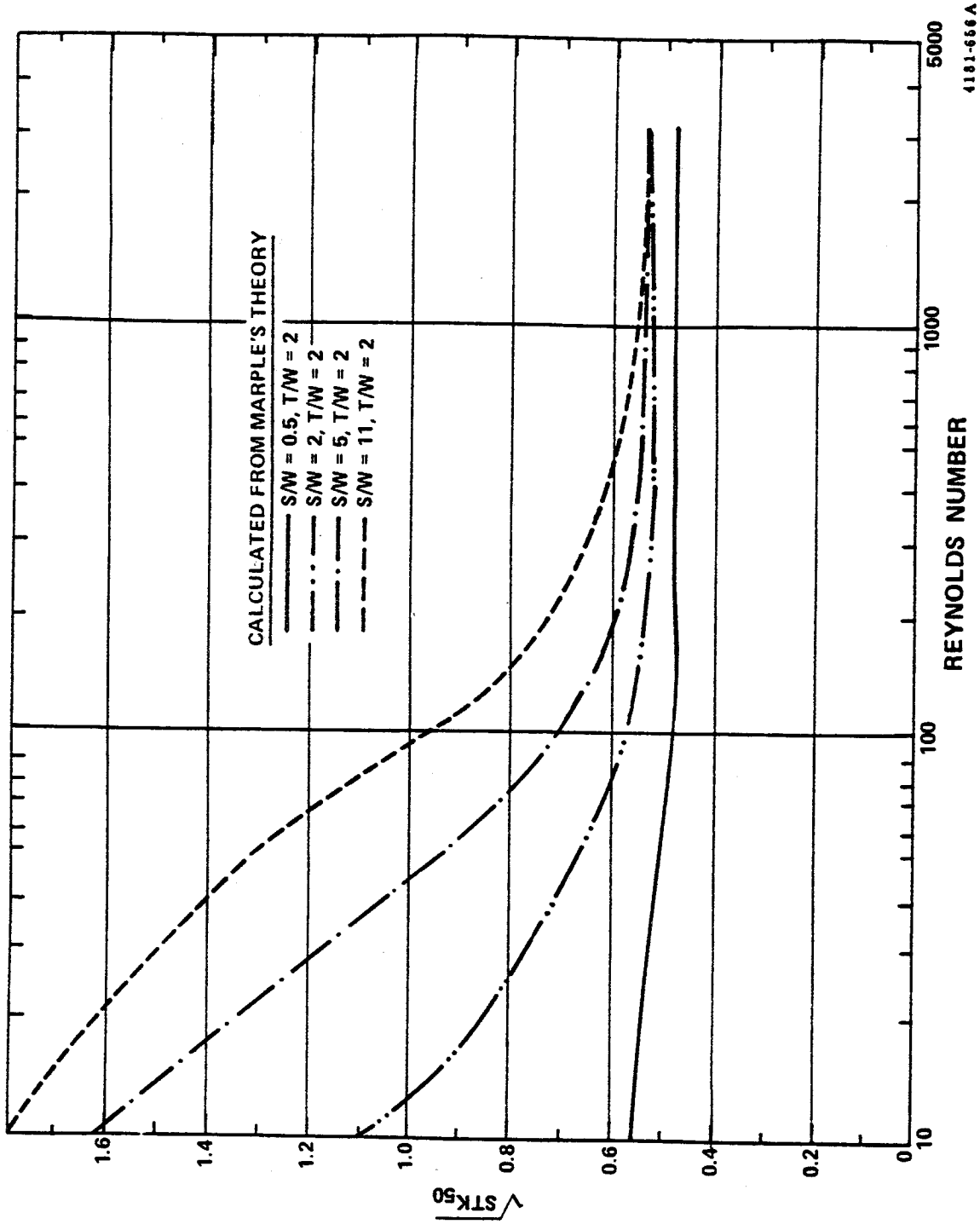


Figure 3-7. Theoretical variations with jet Reynolds number of impactor stage cut-diameter parameters ($\sqrt{STK_{50}}$) (Farthing, 1983).

3.2.3 Effect of Gas Compressibility

The pressure drop across some impactor stages can be appreciable, several inches of mercury in some cases. Even when individual stage pressure drops are low, the cumulative drop through a complete impactor is usually too great to ignore. The stage pressure drops lead to two problems. First, the volumetric gas flow at succeeding stages increases as the pressure is reduced and this increase must be accounted for in the calculation of jet velocities, etc. Second, because the upstream and downstream pressure can be significantly different the question arises as to what are the proper conditions to use in calculating the jet velocity, slip correction factor, etc. for any one jet. That is, should the jet inlet (upstream) or outlet (downstream) conditions be used?

Accounting for the gas expansion to obtain the correct volumetric flow rates at the inlet to each stage is a fairly simple matter. Individual pressure taps for each stage could be used to measure the pressures but implementing such a scheme would be quite cumbersome. Fortunately, stage pressure drops can be estimated with sufficient accuracy using orifice or nozzle flow equations providing that the Mach numbers are not too high. This condition is normally met in source test cascade impactor operations.

Even though the jet inlet and outlet pressures can be estimated with sufficient accuracy by standard flow equations, we are still left with the question of whether to use upstream or downstream conditions in the calculations of the parameters related to the stage D_{50}'s. Flagan (1981) modeled the behavior of impactor stages operating at high pressure drops in a manner similar to that used by Marple (1970), but using the assumption of inviscid, compressible flow rather than viscous, incompressible flow. In this work, pressure drops including values substantially larger than those needed to produce sonic jets were investigated. The results of the flow field calculations indicated that the pressure in the jet impingement region is very near the upstream stagnation pressure. Even at conditions under which the downstream pressure was less than 20% of the upstream pressure the pressure in the impingement region was greater than 75% of the upstream stagnation pressure. Pressure recovery in the impingement region was found to be almost complete for subsonic flows. Modeling of particle trajectories and stage efficiencies showed that when the impaction parameter was defined in terms of the upstream stagnation conditions, it was only weakly dependent on the pressure ratio or jet Mach number and the value of the impaction parameter for 50% collection efficiency agreed with the results from the incompressible flow model. This was not the case if downstream conditions were used.

3.2.4 Verification of Impactor Theory

Before the theoretical models of impactor behavior can be used in the treatment of data they must be verified experimentally. Verification of the models require laboratory calibrations of impactor stages whose designs span a wide range of variation in each of the important parameters in the model. Several such studies have been carried out by a number of researchers and the more important results of these investigations are summarized in the following paragraphs.

One of the most difficult tasks in the calibration of particle sizing devices is the generation of suitable test aerosols. Primary calibration standards should be uniform spheres of precisely known diameters and densities. Detailed treatment of the generation of such particles is beyond the scope of this document but brief descriptions of the two most common techniques will be provided.

Polymerization of certain plastics in liquid suspensions can be controlled to produce particles having a very narrow range of sizes. Under proper conditions it is possible to form hydrosols (particles in liquid suspensions) in which the standard deviation in particle diameter is on the order of one percent. Hydrosols of this type are manufactured and marketed in a large number of sizes from below one tenth of a micrometer to several micrometers by the Seragen Diagnostics Division of Seragen, Inc. Aerosols (particles in gaseous suspension) can be made from the hydrosols by nebulizing the liquid suspensions. (Nebulization is commonly called "atomization".)

Another technique commonly used to generate uniform particles is based on the manner in which a liquid jet breaks up into small droplets. The droplets formed by the breakup of a liquid jet issuing from a small opening tend to be fairly uniform in size as a result of wave phenomena in the jet. If an oscillator and piezo-electric crystal are used to induce pressure perturbations in the fluid at the jet at a frequency near that of the natural breakup wave, the jet can be made to form very uniformly sized droplets. Such particle generators are known as vibrating orifice aerosol generators. The geometric standard deviation of the aerosols produced by these devices is typically about 1.04 (or 68% of the liquid is contained in droplets whose sizes are within four percent of the median). The size of the droplets made in this fashion is set by the properties of the liquid used, the size of the orifice used to produce the jet, and the oscillator frequency. Typically the droplet diameters will be about twice the orifice diameter. By dissolving a suitable solid or liquid aerosol material in a volatile solvent, uniform particles of the solute can be made over a broad continuum of sizes. This is accomplished by adjusting the concentration of the solute in the solution, thus altering the size of the residual particle after evaporation of the solvent from the initial droplet.

Impactor stage collection efficiencies are measured by establishing the desired operating conditions (e.g., flow rate, temperature, etc.) and then introducing the test particles. Online particle counters may be used to directly measure particle concentrations upstream and downstream of the jet/collection plate combination (impactor stage) from which collection efficiencies may be calculated. Alternatively, the aerosol passed by the stage may be collected by a filter after which the amounts collected and passed by the stage can be measured gravimetrically or by other means such as solvent washing of the surfaces followed by chemical or spectroscopic analyses of the washes.

Detailed studies of impactor stage efficiency curves and comparisons with the predictions from theoretical models have been carried out by Mercer and Stafford (1969), Rao (1975), Cushing et.al. (1976, 1979) and Farthing (1983). Results of experiments by Mercer and Stafford are shown in Figures 3-8 together with Marple's theoretical curves. The results of similar experiments by Rao are shown in Figures 3-9 and 3-10. The impactors used in each of these sets of experiments were single jet, round hole impactors operating at relatively small jet-to-plate separations and relatively high Reynolds numbers. In these figures the uncertainties in the measured efficiencies are on the order of seven percent and the uncertainties in the square roots of the particle Stokes numbers are on the order of three percent. Measured stage collection efficiencies for a rectangular slit type impaction jet operated at an intermediate jet-to-plate spacing and high Reynolds number were reported by Felix et.al. (1982). In all of the foregoing examples the measured and theoretical curves were found to be very similar qualitatively and to differ by only a few percent - typically two to three percent - in the value of the square root of the Stokes number at 50% collection efficiency. Figures 3-11 through 3-13 show results obtained by Farthing for round jet impactors operated at greater jet-to-plate spacings and lower Reynolds numbers than were tested by Mercer and Stafford or Rao. Again, the results are in good agreement with the theoretical predictions, both qualitatively and quantitatively, to Reynolds numbers of about 50. At lower Reynolds numbers the theoretical model appears to underpredict the measured values of Stokes numbers for 50% collection efficiency.

Verification of the appropriateness of using upstream rather than downstream conditions to define the impaction parameter was obtained by Flagan (1982) using data from Hering et.al. (1978). Figure 3-14 illustrates the behavior of the value of the impaction parameter for 50% collection efficiency versus the stage pressure ratio as predicted from theory compared to measured values obtained by Hering et.al. McCain and Ragland (1982) reached similar conclusions in a calibration study of a low pressure impactor designed for sizing submicron particles.

3.3 Non-Ideal Behavior and Interferences

Although the performance of actual impactor stages can be well described and predicted by the theoretical model described in the last sections, certain elements of the model are incomplete and some physical phenomena are not treated. Among these missing elements are the effects of gravity, electrostatics, particle charge, turbulence, and particle rebound. The potential magnitude of errors arising from these items and, in some cases, means of ameliorating them are discussed in the following paragraphs.

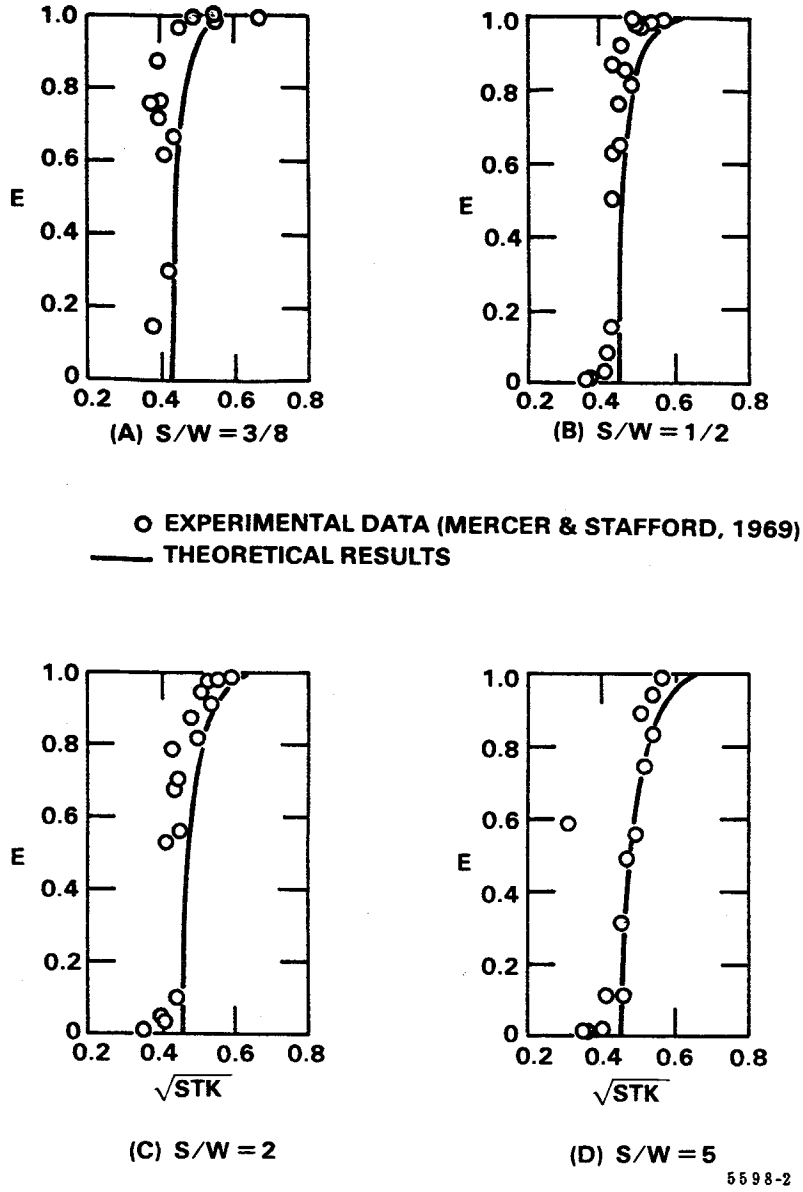


Figure 3-8. Comparisons of theoretical and experimental efficiencies of the round impactor (Marple, 1970).

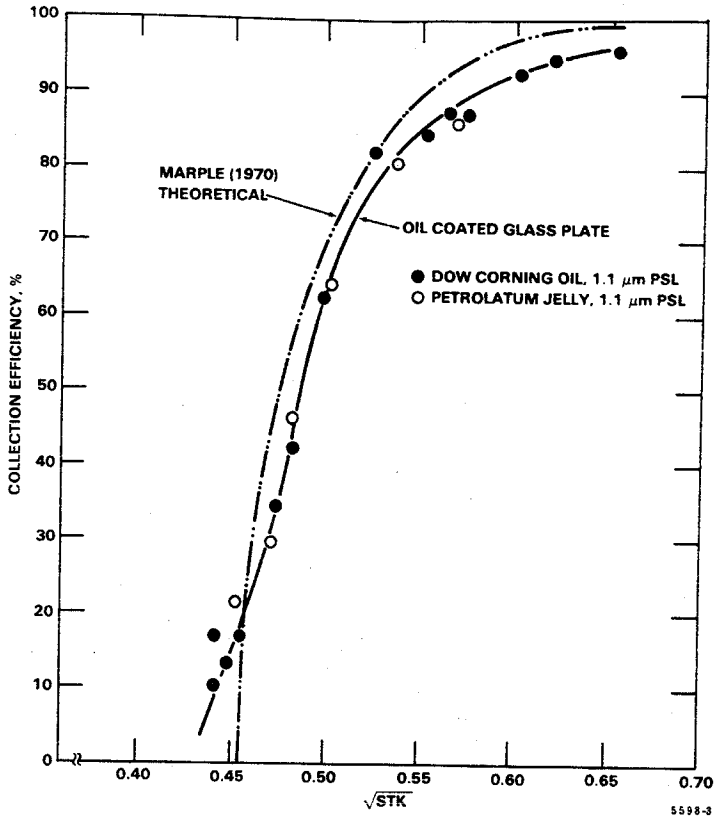


Figure 3-9. Measured and theoretical impactor collection efficiency with oil coated glass plate. S/W = 1.7 and T/W = 2.0 (Rao, 1975).

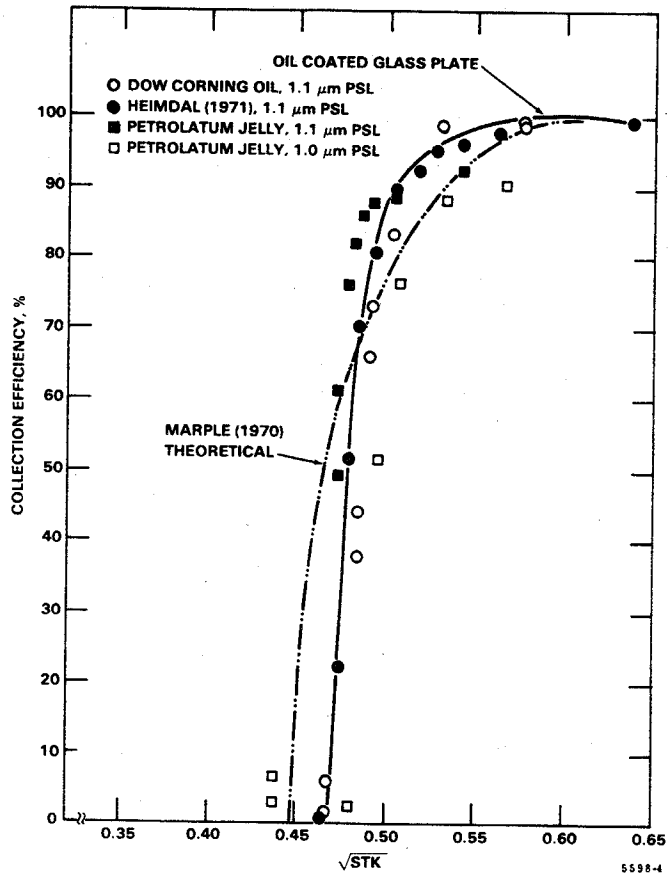


Figure 3-10. Measured and theoretical impactor collection efficiency with oil coated glass plate. S/W = 0.94 and T/W = 1.0 (Rao, 1975).

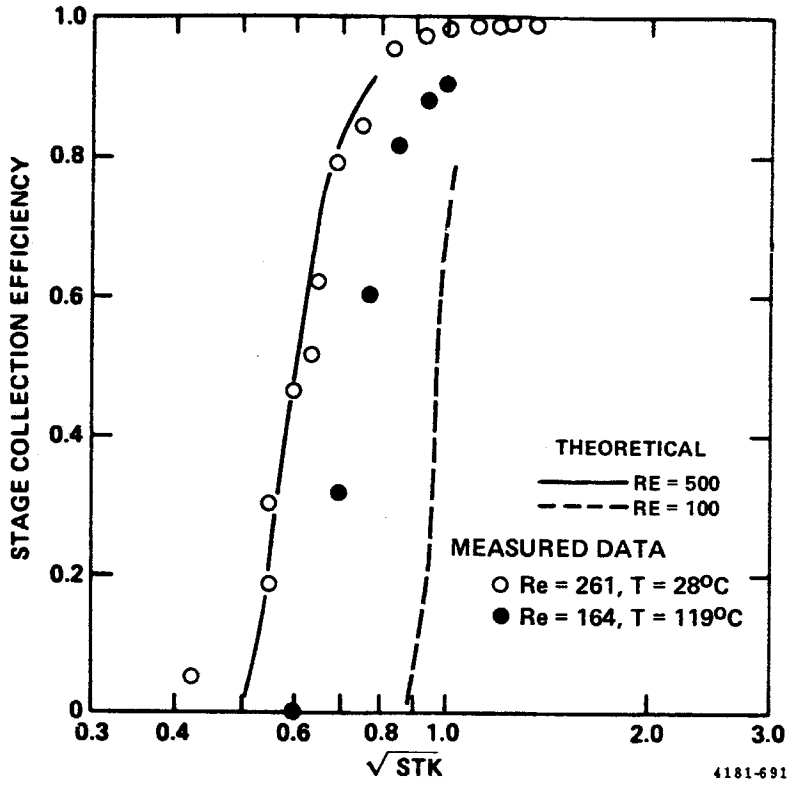


Figure 3-11. Measured and theoretical impactor collection efficiency. For theoretical curves, S/W = 11 and T/W = 2; for measured data S/W = 9 and T/W = 2.5 (Farthing, 1983).

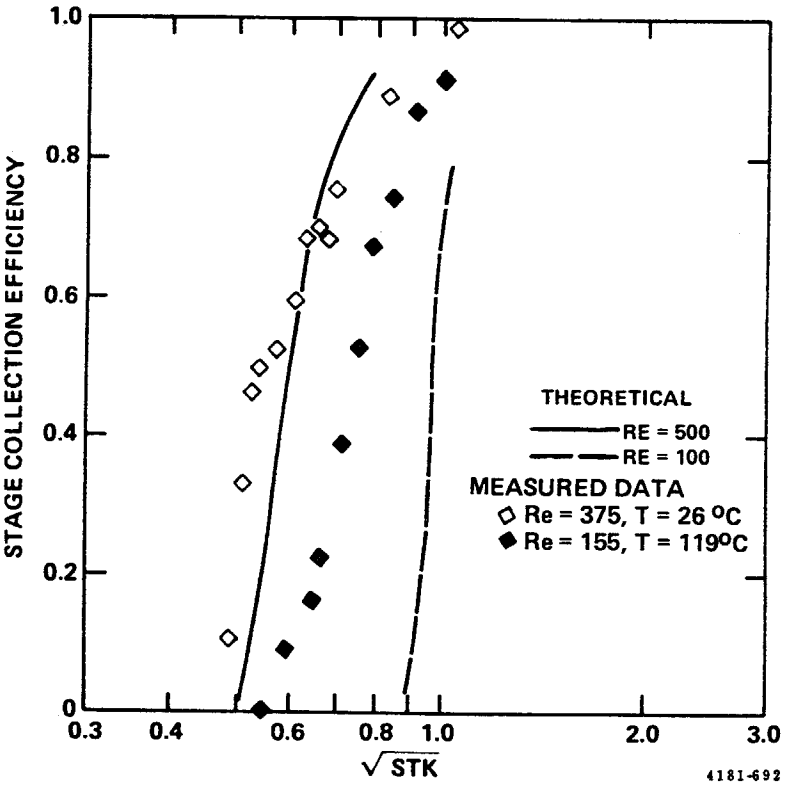
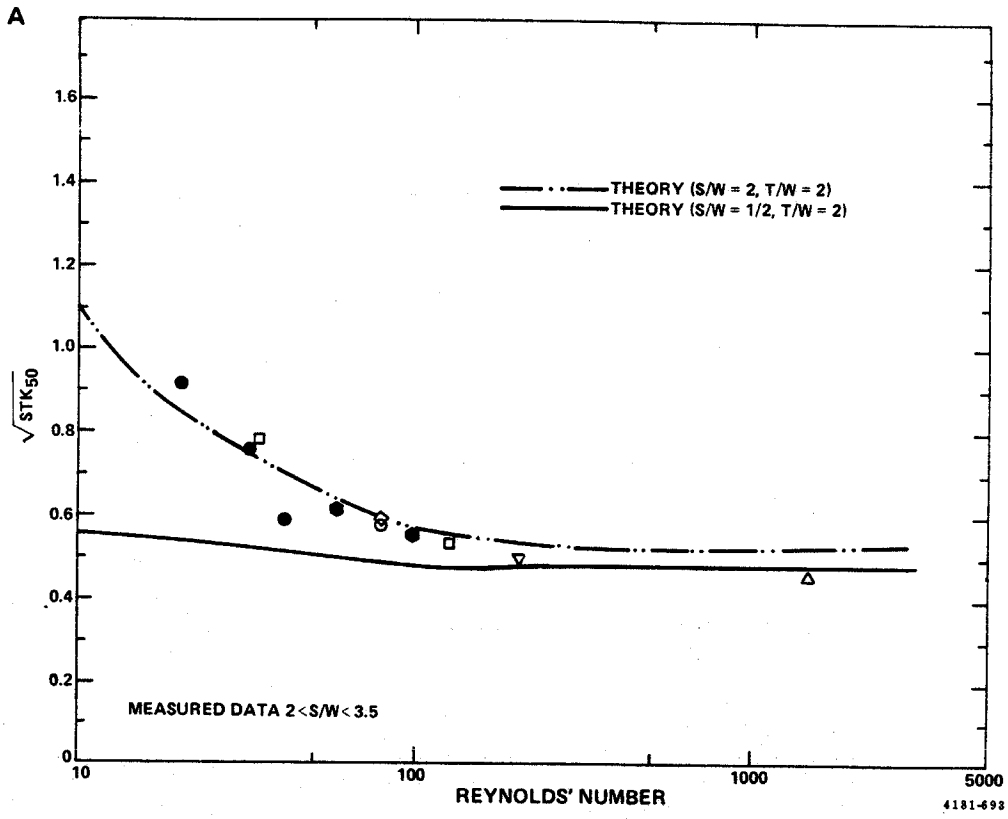


Figure 3-12. Measured and theoretical impactor collection efficiency. For theoretical curves, S/W = 11 and T/W = 2; for measured data S/W = 11 and T/W = 3 (Farthing, 1983).



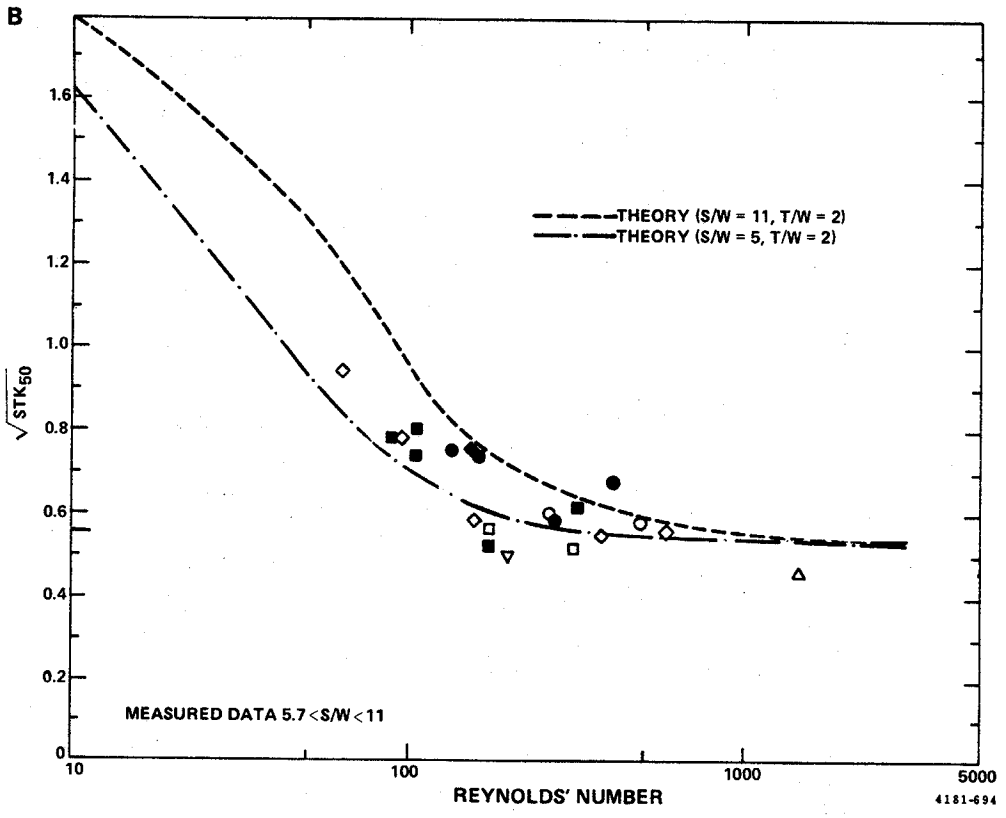
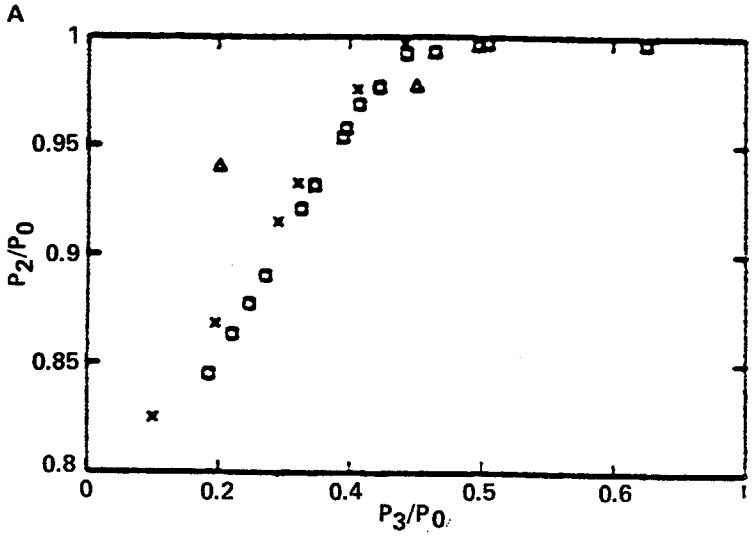
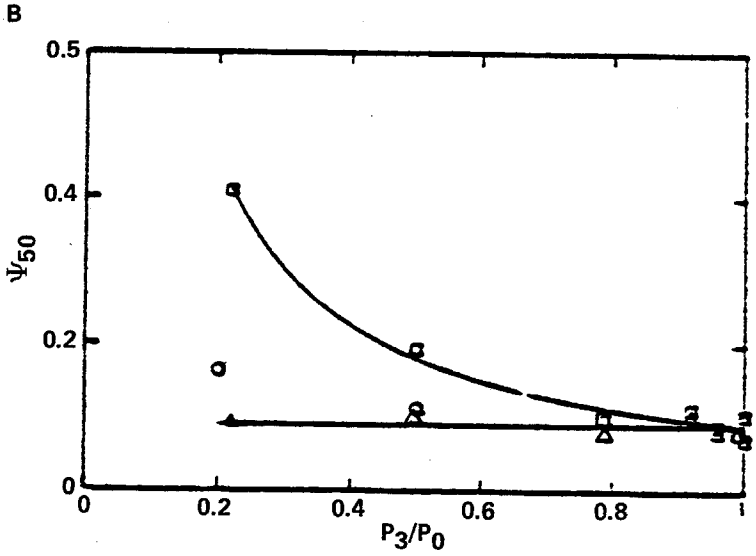


Figure 3-13. Measured and theoretical $\sqrt{STK_{50}}$ versus impactor jet Re. Measured data is from stages with S/W as shown (Farthing, 1983).



DIMENTIONLESS STAGNATION POINT PRESSURE VERSUS OVERALL PRESSURE RATIO. EXPERIMENTAL MEASUREMENTS MADE ON CALTECH LOW-PRESSURE IMPACTOR (× AND □ ARE EXPERIMENTAL MEASUREMENTS; △ IS THEORY).



IMPACTION PARAMETER VERSUS PRESSURE RATIO FOR THE CALTECH LOW-PRESSURE IMPACTOR. (□ - Ψ_{50} CALCULATED BASED ON DOWNSTREAM PRESSURE, △ - Ψ_{50} CALCULATED BASED ON STAGNATION PRESSURE - BOTH FROM MEASUREMENTS. O - Ψ_{50} CALCULATED FROM THEORY BASED ON STAGNATION PRESSURE.

5598-40

Figure 3-14. Impaction zone pressure versus upstream/downstream pressure ratio and variation of Ψ_{50} with pressure ratio. (P_2 = stagnation pressure, P_0 = inlet pressure, P_3 = downstream pressure.)(Flagan, 1982)

3.3.1 Particle Bounce

In the theoretical model of impactor performance, it is assumed that any particle which contacts the collection surface will be retained by the surface. However, as is commonly observed in sand-blasting operations, this assumption is frequently invalid. In the case of impactors, beyond the qualitative information that particles stick when striking a surface at low speeds and bounce at high speeds, little is known about the bouncing or sticking of particles (Rao, 1975). If a particle strikes the collection surface and bounces, it remains entrained in the gas stream and will be collected in a subsequent part of the sampler, resulting in bias and error in the measured size distribution.

For particles smaller than 10 μm, it has been found that although Van der Waals forces, electrostatic forces, and capillary forces in liquid bridges can all play a role in particle adhesion, the dominant force is almost always the Van der Waals force (Jordan, 1954; Löffler, 1968). Even for a 10 μm particle possessing a relatively high charge of 1000 elementary units, the Van der Waals forces are about 100 times as great as the electrostatic forces when the particle is in contact with a surface.

According to Dahneke (1971) particles will bounce if the incident velocity, v_p, is great enough that

$$v_p > \left[\frac{2G}{m}\left(\frac{1 - e^2}{e^2}\right)\right]^{1/2} \qquad (3\text{-}4)$$

where

G = particle-surface interaction energy or the depth of the potential well as seen by the incoming particle,

m = mass of the particle,

e = coefficient of restitution.

The depth of the potential well for a sphere of diameter D_p adhering to a flat surface is

$$G = \frac{A\, D_p}{12\, z_o} \qquad (3\text{-}5)$$

where

A = Hamaker-Van der Waals constant, generally of the order of 10^{-12} ergs

z_o = distance between adhesion partners, typically 4 Å (4×10^{-10}m).

From Equations (3-4) and (3-5) we find that the critical velocity is inversely proportional to the particle diameter.

It should be noted here, of course, that this theory applies only to ideally smooth surfaces of adherents. In case of elastic flattening of the sphere and/or indentation of the flat surface, the adhesion energy, G increases substantially.

The magnitude of the potential problem introduced by particle bounce is illustrated in Figures 3-15 and 3-16 which show calibration results obtained by Rao (1975). The test particles used in generating these data were dry solids (polystyrene latex beads). In each figure we find that the experimental curves of collection efficiency versus $\sqrt{STK}$ fall very close to the theoretical curves if the collection surface was coated with a material that could absorb the impact energy and act as an adhesive to retain particles which struck it. On the other hand, collection efficiencies using uncoated glass plates fell close to those for the coated plates at the lower Stokes numbers (lower jet velocities) but for values above some critical jet velocity (or Stokes number) the curves broke away from those for the coated plates. For Stokes numbers above the break collection efficiencies failed to reach even 50%.

Cheng and Yeh (1979) proposed a guideline for impactor operation intended to eliminate particle bounce problems. Based on numerous experiments with a number of types of dry "bouncy" particles they suggested that if the product of the jet velocity and aerodynamic diameter of the particles impacting on each stage were kept to values below about 5 μm-m/s, the assumption that particles adhere to the collecting surface on contact would be valid. In practice it is impossible to adhere to this guideline without forcing operation at very low Reynolds numbers by using very large numbers of quite small jets. As previously discussed, impactor performance becomes less well predicted at very low Reynolds numbers than is desirable; moreover, the manufacturing costs for making impactors would rise considerably, if this option were taken.

The close agreement between the theoretical and experimental performance curves shown in the two previous figures, when oil coated impaction plates were used, lies at the heart of the most widely used technique for eliminating particle bounce problems. That is the use of surface coatings to absorb the impact energy and retain the particles. Various silicone and hydrocarbon-based oils, greases, polymers, and rubbers have been used successfully as coatings by one or another group of impactor users. A material which wets and that will wick up through the collected particles to maintain a fresh surface coating is desirable. However, the coating must not be able to flow or it will be subject to loss to other surfaces of the impactor while being transported or used. This results in the use of coating materials which are selected for a compromise in particle wetting, wicking, and retention with enough stiffness to remain in place on the collection substrate in use. Thus the $V \cdot D_{50}$ products for the impactor stages must be limited even when coatings are used; albeit at higher values than for bare surfaces. (The jet velocities must also be kept low enough to insure that the coating is not eroded by the jet.) The key requirements are the ability of the coating to simultaneously maintain stability in weight and the needed physical properties for particle adhesion.

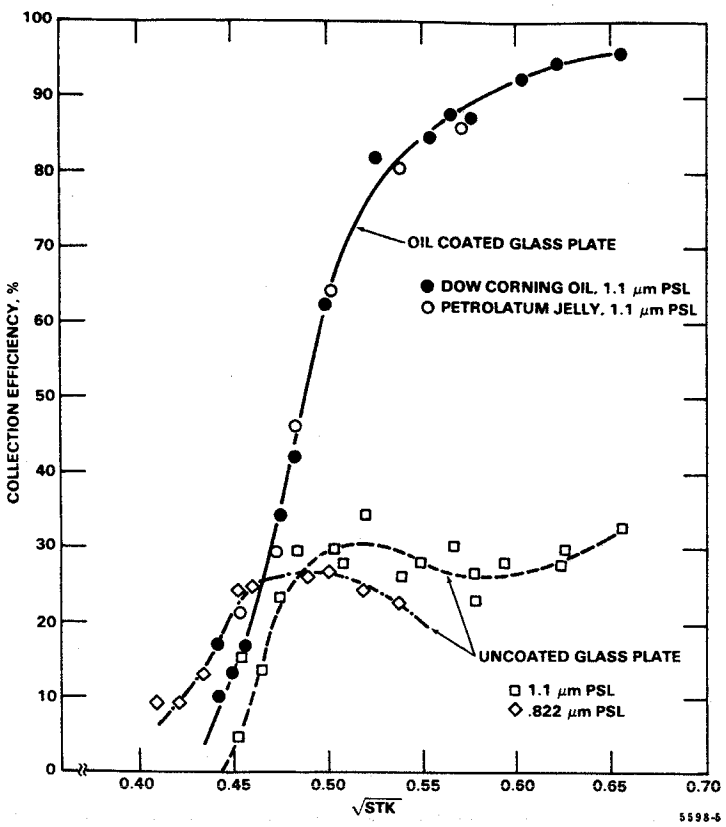


Figure 3-15. Collection efficiency of impactor with oil coated glass plate, and uncoated glass plate. S/W = 1.7 and T/W = 2.0 (Rao, 1975).

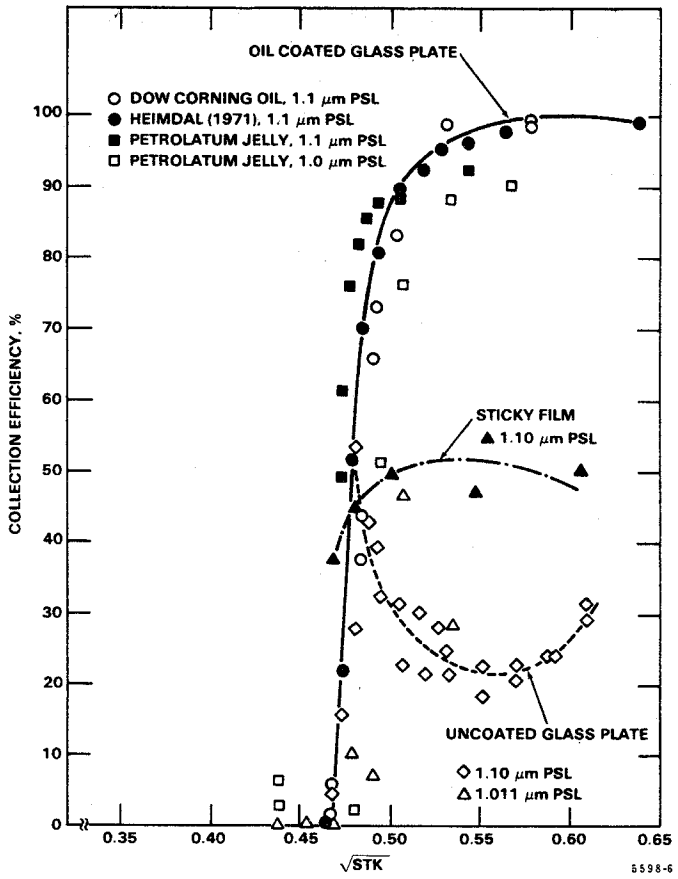


Figure 3-16. Collection efficiency of impactor with oil coated glass plate, uncoated glass plate, and sticky film. S/W = 0.94 and T/W = 1.0 (Rao, 1975).

It is important that a material be used only within a specified temperature range. There are several reasons for restricting the temperature range. Among these are weight loss and/or degradation of the needed physical properties at excessively high temperatures and the fact that many materials become too hard at temperatures below the recommended limit. An example of the latter effect is shown in Figure 3-17. This figure illustrates the measured collection efficiency by particle size for the same impactor stage and sampling conditions using two different coatings. The measurements were made at laboratory temperatures. Under these circumstances, the first coating petroleum jelly was soft and "sticky", while the other (Apiezon H) was too hard at low temperatures. Apiezon H is commonly used in flue gas sampling for temperatures in the range from 150 to 200°C.

To date, no coating materials have been identified which can be used at temperatures above about 230°C. Thus, alternate solutions to the bounce problem were sought to avoid the necessity of limiting the $V \cdot D_{50}$ product to very low values. The use of fiber mat surfaces has been the most successful of these to date. If a fiber mat such as a glass or quartz fiber filter is used as a collection surface, particles which do bounce have a reasonable probability of being deflected into the depths of the mat and being retained rather than rebounding directly back into the gas stream. This technique has been demonstrated to reduce particle bounce sufficiently to permit useful data to be obtained. Figure 3-18 shows actual stage collection efficiency curves for an Andersen cascade impactor sampling ambient air and dry solid particles (Rao, 1975). Three sets of curves are shown in the figure: one for which oil-coated collection surfaces were used; one for which bare metal surfaces were used; and one for which glass fiber filter surfaces were used. It is quite apparent that the performance with bare metal surfaces is totally unacceptable. However, the performance with glass fiber substrates is adequate, even though the measured efficiencies did not quite reach 100% for any size at any stage. As the $V \cdot D_{50}$ product for an impactor stage is increased, the maximum collection efficiencies obtainable with fibrous substrates decreases, thus limits must also be set on $V \cdot D_{50}$ products for operation with fiber substrates. It should be noted that the stage D_{50}'s in Rao's data shifted to smaller diameters and the sharpness of the cut was reduced when the glass fiber surfaces were used. The relative shift in D_{50} was not constant from stage to stage and cannot be predicted by any currently available theory. Thus if fibrous substrates are to be used, the impactor should be calibrated with these substrates at conditions similar to those under which the sampling will take place.

Aerodynamic D_{50}'s are plotted versus stage jet velocities in Figure 3-19 for a number of cascade impactors. These velocities and D_{50}'s represent the values that would result if the impactors were operated at their respective design flow rates at laboratory conditions. The shaded area in the figure represents the range in which the $V \cdot D_{50}$ products would meet the criterion set by Cheng and Yeh for operation with bare collection surfaces. As can be seen, none of the impactors meet the criterion for all stages and some do not meet it for any of their stages. Extensive laboratory calibrations were performed by Southern Research Institute of each of these impactors. Calibrations of the Andersen, Flow Sensor, and Sierra impactors were done with glass fiber substrates. The results of this work revealed that the performance of the

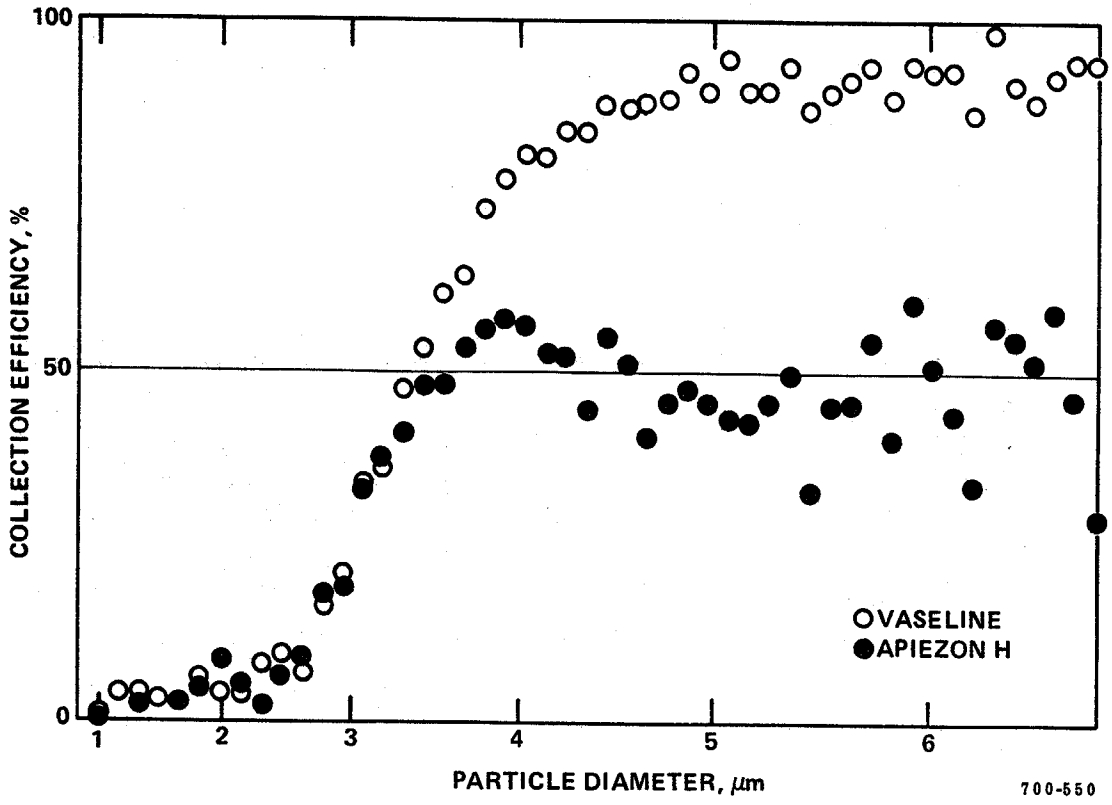


Figure 3-17. Measured collection efficiency at room temperature of an impactor stage with two substrate greases. Significant particle bounce effects are seen with Apiezon H, which at room temperature is far below the softening point (McCain et al., 1985).

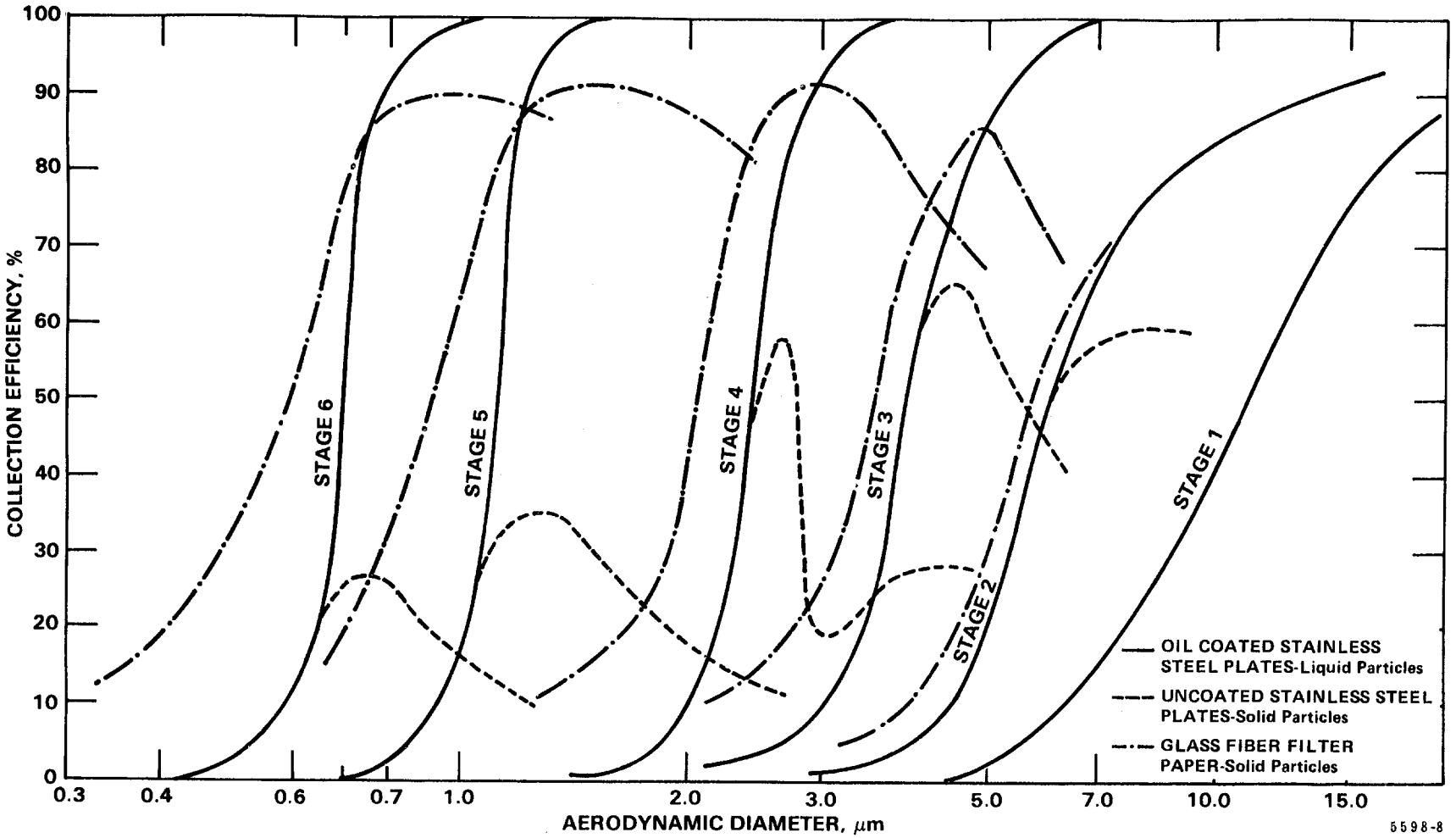


Figure 3-18. Collection characteristics of the Andersen sampler (Rao, 1975).

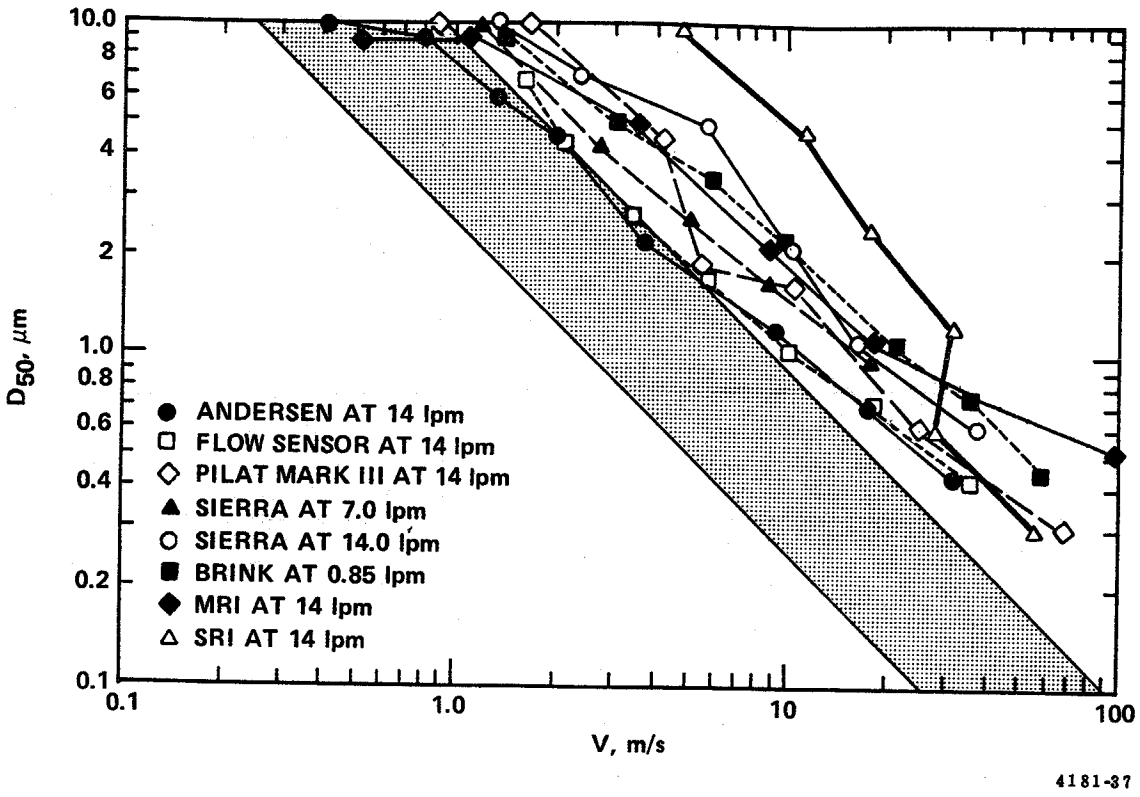


Figure 3-19. Stage D_{50} versus stage jet velocity for various round jet cascade impactors. Grayed area satisfies no bounce criterion of Cheng and Yeh (1979).

Sierra impactor was unsatisfactory because of excessive particle bounce when it was operated at a flow rate of 14 lpm. The performance of the Flow Sensor and Andersen impactors at that flow rate was satisfactory, and when the flow rate of the Sierra impactor was reduced to 7 lpm its performance became satisfactory. The Brink, Pilat Mark III, and MRI impactors were all tested with grease-coated substrates as was an experimental impactor designed by Southern Research Institute. For the Brink and MRI, performance was marginal with respect to particle bounce at the conditions of the tests. The experimental SRI impactor had excessive bounce even when a normally effective grease was used. As a result of these experiments, general guidelines were developed for impactor operation that are based on the $V \cdot D_{50}$ products for the individual stages. For bare metal as a collection surface, the $V \cdot D_{50}$ product should not exceed 10 μm-m/s at any stage and should probably be kept to values below 5 μm-m/s. For fibrous collection surfaces, the $V \cdot D_{50}$ products should not exceed 15 μm-m/s. For grease-coated substrates, the product should not exceed 25 μm-m/s. Adherence to these guidelines should result in acceptable control of particle bounce under virtually all circumstances. In instances in which the particulate matter is sticky, these limits may be unduly restrictive and operation at conditions which result in larger $V \cdot D_{50}$ products may still produce acceptable performance.

3.3.2 Catch Limits

The quantity of particulate matter which can be collected on a single stage is limited by factors which depend on the detailed geometry of the stage, the properties of the particles being sampled, and the properties of the collection surfaces. If the deposits of collected particles become too large they become subject to being reentrained, resulting in the transfer of particles from the proper collection stage to one or more subsequent stages. Such reentrainment will obviously bias the results and, if severe, will totally invalidate them. Limits to stage loadings that will insure that reentrainment poses no problem are difficult to quantify as they depend on the adhesion and cohesion properties of the particles, as well as the properties of the collection media and particle/media interactions. However, extensive laboratory and field experience has resulted in the use of the figure of 15 mg as a good guideline target for the maximum load to be collected by any one impactor stage.

A further limitation in stage loading is set by the fact that as material collects under a jet the effective jet-to-plate spacing is reduced. This can result in an unacceptably large shift in the stage D_{50} as the sample collection takes place, depending on the initial spacing and the jet Reynolds number. In extreme cases when sampling very sticky particles, the impacted particles collect in a rod-like structure which can bridge the gap between the collection plate and jet and actually plug the jet.

In sampling sources at which the particle size distribution is dominated by particles whose diameters are larger than the cutoff diameter of the first impactor stage, a method is needed to provide a means to avoid overloading the first stage before sufficient material for measurement can be collected on suceeding stages. Several forms of high capacity precollectors are available for this purpose. Some of these are small cyclonic separators while others are

impaction devices which are designed to utilize gravity and baffling for retention of large particles. All of the devices made for this application have load capacities of several hundred milligrams or more.

3.3.3 Interferences

Both grease and fibrous impaction surfaces are subject to chemical and/or physical changes when exposed to industrial flue gases. These can be in the form of weight gains or losses which may be comparable to or larger than the gains caused by the collected sample or they may, in the case of greases, alter the surface properties so that the impacted particles are not retained.

In the case of fibrous media, reactions with vapor phase components of the sample stream can result in weight losses or gains. Most commonly, such reactions result in weight gains; however, some may result in losses (e.g. reactions with low concentrations of HF in some process exhausts). SO_2 is a common constituent of flue gases from combustion processes which can react with glass fiber materials to form sulfates on the fiber surface. Such reactions can lead to weight changes of several milligrams while the weight of the sample collected on an impactor stage is typically only a fraction of a milligram to a few milligrams. Because of its ubiquitous nature and the severity of the problem, special treatments have been devised to deal with SO_2 reactions with glass fiber media. Many of the reactive properties of glasses are related to impurities and non-silica components contained in them. Barium oxide is one such component that is especially susceptible to reaction with SO_2. Quartz fiber materials are far less subject to problems resulting from chemical reactions but are not as mechanically strong as borosilicate glasses and consequently may not be useful in some applications. In addition, mechanical loss of fibers, if permitted to occur, can lead to unacceptably large errors due to weight loss or transfer from one stage to another downstream.

Greases and similar coatings are subject to weight changes from several mechanisms. If the grease flows too freely at the operating temperature, some can be blown off a stage from excessive jet velocities or be transferred to other surfaces simply by flowing off of the impaction substrate. Evaporation of volatile constituents can also lead to weight loss. On the other hand, chemical reactions with gas phase constituents of the sample stream can result in weight gains that are unrelated to collected particulate matter. In addition, temperature and chemically induced changes in the physical properties of the coating can make it unsuitable for its intended purpose of particle retention.

Because of the effects discussed above, it is imperative that the collection media to be used in a sampling program be tested for suitability for the particular application before the actual sampling is begun. It is also advisable to periodically recheck the selected impaction substrate materials during extended sampling programs at a single source.

3.3.4 Sampling Nozzle and Inlet Effects

Particle size dependent effects in the sampling nozzles and inlet transforms used to withdraw the sample from the gas stream to be measured and deliver it to the impactor stages must be accounted for in the measurement process. Losses in bends, expansion zones, interconnecting tubing, and housings can arise from inertial deposition, turbulent deposition, and gravitational settling - none of which are accounted for in the theoretical treatments of impactors.

First of all, settling losses are excessive in horizontal probes of the lengths required for stationary source sampling, so impactors must be operated in situ. Even when impactors are operated in stack, losses in the inlet sections of the sampler can be significant and must be accounted for in impactor measurements. Perhaps the most common error here lies in the easily overlooked fact that the sampling nozzle always acts as an impaction jet. Some, but not all, impactors are designed to make use of this. But in all cases, the nozzle, whose tip size must be correct for isokinetic sampling conditions, becomes the first impaction jet - whether by design or not.

Historically, the recommended practice for sampling with cascade impactors has been to attach the impactor to the probe with a 90° bend between the impactor and probe axis allowing the impactor axis to be aligned with the gas stream being sampled. In many instances, the geometry of the sampling ports would not permit insertion of such a configuration thus a "gooseneck" nozzle was used so that the impactor could be aligned with the probe. However, it has been found that the trajectory of the sample into the first size separating stage must be parallel to the flow stream from which the sample is being taken. The use of "gooseneck" or similar bent nozzles to turn the sample flow into the probe in the fashion used with Method 5 cannot be permitted for size distribution measurements. If such a bent nozzle is used, it effectively becomes a poorly-behaved impaction stage preceding the particle separator and can cause large changes in the apparent size distribution (Felix and McCain, 1981; Knapp, 1980). Figure 3-20 illustrates the predicted separation diameters for 90° nozzles over the range of sampling conditions that are commonly encountered in industrial source sampling. Cutoff diameters for such nozzles under typical conditions range from about 2 to 7 μm. Results obtained using such nozzles are not valid for diameters larger than the cutoff diameter of the nozzle. Recently, manufacturers have begun to offer samplers with the first stage oriented at a right angle to the main body of the sampler or add-on precollectors with a right angle orientation. These arrangements permit the impactor assembly to be mounted co-axially with the probe while maintaining the direction of flow parallel to the sampled stream up to the first inspection stage.

Even when 90° nozzles are not used, impaction losses in impactor inlet stage can be a problem. The nozzle tip sizes required for isokinetic sampling are typically small enough that the effective stage D_{50} of the nozzle is only a few microns as was illustrated in Figure 3-20. To allow size fractionation at larger particle diameters, the standard practice in the design of impactors for source testing is to gradually expand the nozzle and/or transform to the first "standard" collection stage. By permitting the sample to decelerate before

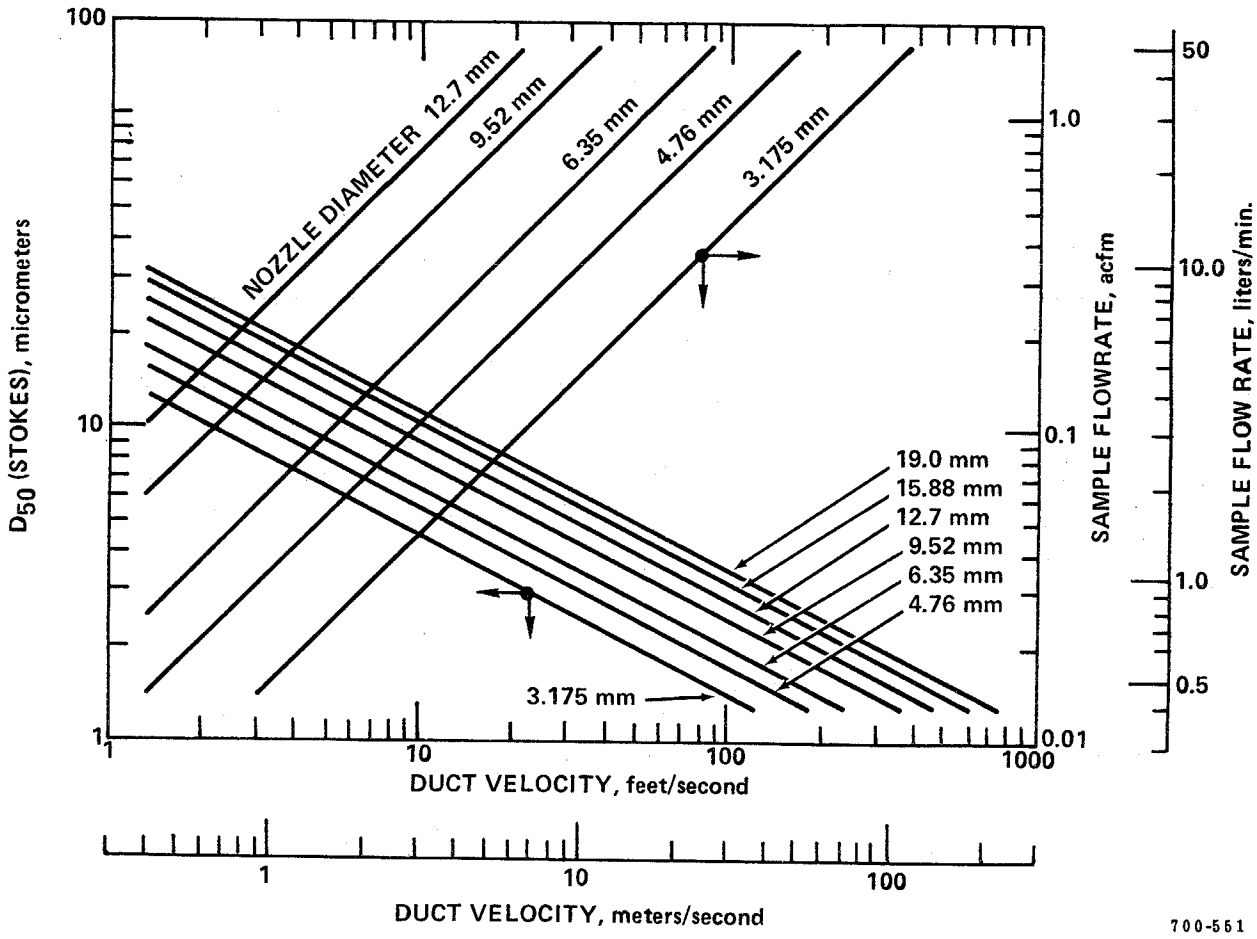


Figure 3-20. Curves to predict the physical cut-diameters (Stokes D_{50}) of 90° sampling nozzles for various nozzle sizes and sampling conditions. Calculated for 150°C and 2.4 g/cm^3 particle density; for aerodynamic cut-diameter multiply Stokes D_{50} by 1.55 (McCain, et al., 1985).

reaching that stage these designs attempt to raise the effective D_{50} of the inlet to a value that does not undercut the first stage or stages. In some cases the nozzle itself is flared over a short enough distance to make settling losses acceptable and the nozzle exit is used as the first jet. This approach is used in the Pilat impactors and in several of the "Right Angle" precollectors which are on the market. However, the expanding jet geometry has not been modeled and calibrations of this geometry show that the cuts are not predicted at all well by current theory. In other devices such as the Andersen Mark III Stack Sampler and the Sierra stack sampling impactors, long expansion transforms are used. But even though the effective jet-to-plate distances are large, impaction still occurs on the inlet surface to the first jet stage. Moreover, settling losses become quite significant when the devices are operated in a horizontal position. Likewise, the multijet inlet transform of the MRI 1501 impactor is subject to significant impaction losses. The end result of all of this is that the effective value of the impaction parameter for the first impaction stage is much smaller than predicted by theory in all cases. Therefore, calibrations must be used to determine empirical relationships for obtaining the first stage D_{50}'s. These effects also make it very difficult (or virtually impossible) to size particles larger than about 10 to 15 μm with cascade impactors.

3.3.5 Electrostatic Effects

The effect of particle charge on particle deposition in impactors is of potential concern, especially when sampling aerosols that are known or are expected to carry significant unipolar charge levels. Particles exiting a high efficiency electrostatic precipitator (ESP) would fall into this class.

Experiments to quantify the effect of particle charge on particle collection in impactors have been carried out using both monodisperse and polydisperse aerosols (Farthing et.al., 1979). A range of charge levels from neutral to levels about five times greater than would be expected on particles exiting an ESP were used in these experiments. The results showed the following:

1. At moderate charge levels there was no shift in stage D_{50}'s.

2. At high charge levels (5x typical ESP exit charges) there were large effects, primarily in the form of increased wall losses.

3. Grounding the impactor and collection surfaces made the effect of charge greater.

4. The measured size distributions of the same polydisperse aerosol with neutral particles and with moderate charge (comparable to ESP exit charges) were virtually identical.

5. The measured size distributions of polydisperse aerosols showed apparently higher concentrations of large particles and correspondingly reduced concentrations of small particles than the true distribution when the particles were highly charged.

In conclusion, particle charge is not believed to cause serious errors in cascade impactor data under the conditions which might be expected to be found in sampling industrial sources, although errors can be expected if charge levels a great deal higher than those encountered at ESP outlets are met.

3.4 Field Protocol

The following paragraphs provide a summary of the field procedures for the determination of particle size distributions at stationary industrial sources by using cascade impactors. The protocol given may be used for any of the cascade impactors listed in Appendix B (Commercially Available Hardware) of the procedures document. The Pollution Control Systems (University of Washington) Mark V Cascade Impactor with right angle precollector was recommended to ARB as the preferred instrumentation for the Size Distribution Method and the Protocol is specifically aimed at the special features of that device. Little modification is needed to adapt the protocol to the other instrumentation.

3.4.1 Inlet and Outlet Sampling Situations

Most industrial sources utilize a control device to remove particulate matter from the sample stream before discharge to the atmosphere. Sampling at points upstream of the control device is frequently referred to as the inlet sampling environment and sampling at points downstream of the control device is referred to as the outlet sampling environment. With today's high efficiency control devices, collection efficiencies of 99.9% are common. At such a facility the particulate concentration at the outlet is $^1/_{10}$ of one percent of that at the inlet, a difference of 1,000 to 1. Differences of 10,000 to 1 are not uncommon. As one might suspect this can pose a formidable problem when the same sampler is to be used for both sampling environments. The same 50% collection diameters are desired for both environments, so the impactor flow rate must be approximately the same if the same stages are used. Consequently the only remaining control variable that can be adjusted is the run time. If any one of the stages of the impactor overloads particulate matter is transferred down to lower stages (reentrainment) causing the data to be invalidated. The dynamic range between minimum stage loading (reliably measurable weight change $\approx$ 0.2 mg) and the maximum stage loading prior to reentrainment occurring (about 15 mg, dependent on aerosol characteristics, jet velocities, and substrate material) is at best about 75 to 1. If a five minute run time at the inlet of a high efficiency control device (99.99%) resulted in a weight gain of 15 mg on the most heavily loaded stage, the outlet run time would need to be 667 min (11.1 hours) to obtain a weight gain of 0.2 mg on the most heavily loaded stage. Note that this would lead to unreliable weights for all other stages. Most impactors have been designed to require a sample time of about two hours on high efficiency control devices. Consequently the same impactor would commonly overload in less than one minute at the inlet to this same control device. For this reason, some impactors have been designed for inlet situations by using stages which give the desired D_{50} at low flow rates. The need to sample isokinetically together with a practical minimum nozzle diameter of about 1/16 inch, places a lower limit on the impactor flow rate. Low flow rate impactors would require very very long run times if used at the outlet of a high efficiency control device. The solution of the problem is to use different impactors, or impactor configurations for the two environments.

3.4.2 Measurement Principle and Applicability

The protocol addresses the application of cascade impactors to industrial source sampling situations. The technique is valid when the equipment configuration, operational flow rate, and total gas volume sampled are properly selected such that measurable quantities are collected (without overloading) and operational regime limits for Reynolds number and jet velocities are observed. Skilled operators are needed for proper operation of cascade impactors and for carrying out the subsequent analysis of the data. The protocol attempts to set forth procedures which are workable and valid for most commonly encountered sampling situations but it is impossible to address all possible sampling situations. Consequently these procedures are to be considered as recommendations rather than compliance procedures. The skill, experience, and judgment of the user are important factors in the successful application of the method.

3.4.3 Sampling Train

A schematic of the sampling train is shown in Figure 3-21. The right angle precollector and cascade impactor are mounted on the modified probe of a standard Method 5 sampling train. The pitot head normally used on a standard Method 5 sampling train is not used with impactors. The flow metering orifice on the dry gas meter may need to be changed to an appropriate size for the desired impactor flow rate. Since the impactor is operated in-situ the filter/oven section of the Method 5 train is not used. All in-situ components should be constructed of stainless steel for purposes of temperature tolerance, ruggedness, and for resistance to corrosive flue gases. High temperature heating tapes permit the same probe to be used in hot side (>400°F) as well as cold side sampling situations. Method 5 Sampling Trains are available from numerous commercial vendors. The following paragraphs describe the various components of the sampling train.

3.4.4 Right Angle Precollector

In most situations the use of a right angle precollector is essential. The precollector serves to (1) turn the sample stream through a 90° angle and (2) help prevent overloading of first impactor stage. If the port arrangement is such that the impactor can be rotated into flow and the loading and size distribution of the sample stream does not cause overloading problems with the first impactor stage, then the precollector is not necessary. Such is seldom the case, however.

Most industrial sources only have four inch diameter sampling ports and use thick, insulated walls so that clearance is not adequate to permit rotation of the impactor into the flow stream. The curved nozzles (90° Bent and Buttonhook) used with Methods 5 and 17 are unacceptable for use with particle sizing devices because of high particulate losses in the nozzle.

At most sources the mass is concentrated in the larger particles thus overloading of the first stage may occur before minimum detectable weights are obtained on some of the lower stages. The capacity of the upper stages needs to be increased to permit collection of weighable quantities at the lower stages. The precollector provides a means of accomplishing this.

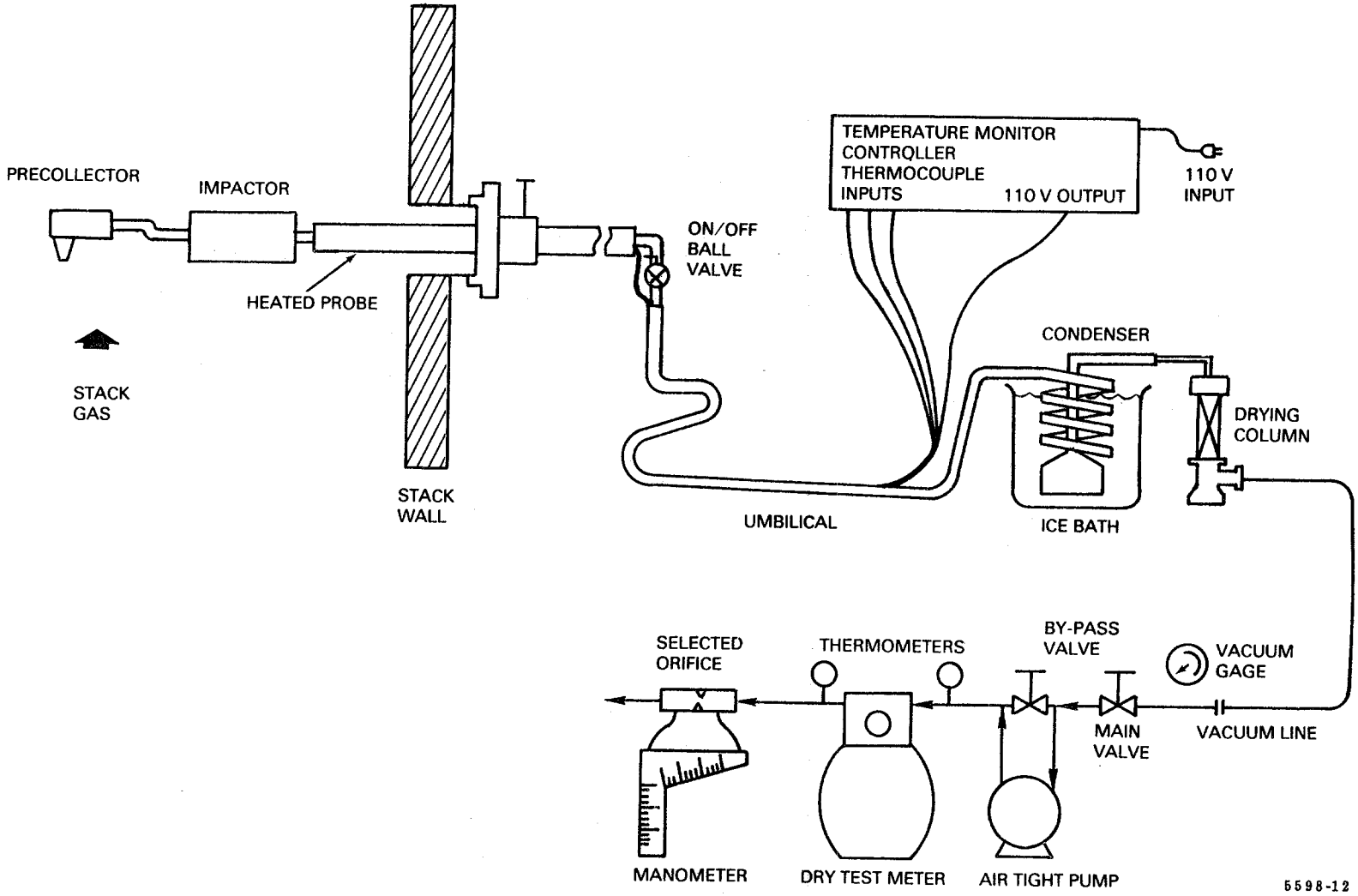


Figure 3-21. Cascade Impactor particulate sampling train for noncondensible particulate (modified EPA Method 5 Train).

3.4.5 Nozzles

When attached to the right angle precollector, the nozzle should not inhibit entry through a four inch diameter port. However, if the impactor can be rotated into flow it may not be necessary to use a precollector. The nozzles should have a sharp leading edge. The inside of the nozzle should have an even taper from the inlet diameter to the correct exit diameter for the particular precollector. It is important that all nozzles have the same exit diameter since this is one of the critical dimensions in the aerodynamic performance of the precollector (inlet jet diameter).

A range of nozzle sizes is needed for isokinetic sampling. The recommended range is from $^1/_8$ to $^1/_2$ inch (3.2 to 12.7 mm) diameter in increments of $^1/_{16}$ inch (1.6 mm). For inlet sampling with a low flow rate impactor, it may be necessary to use smaller diameter nozzles and smaller increments in nozzle diameter. Problems with nozzle pluggage establish a minimum diameter of about 0.0550 inches (1.4 mm).

3.4.6 Cascade Impactor

Appendix B of the Impactor Procedures Document gives a list of current commercially available cascade impactors suitable for use as in-situ stack samplers. All of these impactors are designed with an internal filter holder. The impactor type used must have been calibrated for the configuration to be used (choice of substrate material and stages used) to verify that its performance is predictable. The Pollution Control Systems (University of Washington) Mark V Cascade Impactor is the ARB preferred instrumentation, together with an accessory right angle precollector and nozzle set (EPA/SoRI design). The Mark V impactor is of an in-line design permitting the user to choose appropriate stages for a given sampling situation (inlet, outlet, stack velocity, temperature, etc.).

3.4.7 Flue Gas Composition and Velocity Profile (P_s, B_{ws}, M_s, υ_s)

Once the sampling site is prepared and the equipment is in place, the first action is to determine the Flue Gas Composition using Method 3 (Gas Analysis for Carbon Dioxide, Oxygen, Excess Air, and Dry Molecular Weight) or Grab Sampling Techniques (Fyrite type Analysis) and Approximation Method 4 (Determination of Moisture Content in Stack Gas, Section 3). A pitot traverse (Method 2) must be made in order to determine gas temperatures and velocities over the sampling plane. The gas fractions for O_2, CO_2, and B_{ws}, the molecular weight (M_s), absolute stack pressure (P_s), point velocity distribution $\upsilon_{s_{i,j}}$, average velocity (υ_s) and an initial guess at the flue gas mass loading (c_s, gr/acf), are then used to select the stage configuration, sampling flow rate, nozzle size, and traversing protocol.

3.4.8 Traversing Protocol

In order to obtain a representative measurement one must obtain samples at representative points across the duct (stack) at isokinetic rates. In the case of conventional total particulate testing (e.g., Methods 5 and 17), this is accomplished by dividing the duct into a large number of equal area segments (per Method 1) and obtaining an isokinetic sample at the centroid of each of these areas. In Methods 5 and 17, isokinetic sampling is achieved by selecting a nozzle which is appropriate for the combination of the nominal flow rate at which the sampler is intended to operate and the average duct velocity. Compensation for duct velocity variations is then achieved by adjusting the sampling rate. This procedure cannot be used with inertial particle size classifiers because changes in sampling rates result in shifts in the diameter(s) at which size fractionation takes place.

With a fixed flow rate sampler the following procedure is recommended: establish anisokinetic limits and divide the sample plane (Method 1 Traverse Points) into multiple regions such that all points within a given region may be sampled at a constant velocity and satisfy the anisokinetic limits. Separate runs are then performed for each region. The runs are averaged using a weighting proportional to the total volumetric flow of each region, this average synthesizes a complete traverse. Method 1 procedures are used to define the traverse points and Method 2 procedures are used to determine the velocity at each point.

The suggested criterion for the isokinetic sampling limit is that each point sampled during a run should have a point velocity that is within ±20% of the impactor inlet velocity. Each of the Method 1 traverse points should be sampled, thus if the ratio of the minimum velocity to maximum velocity within the entire sampling plane is greater than about 1.5, multiple impactor runs are required. In the latter event, two or more regions would be selected such that for each region the velocity at every point within the region satisfied the 20% requirement.

Thus for any point i within a given region, the velocity at that point (υ_i) meets the criteria $.8V \leq \upsilon_i \leq 1.2V$ where V is the sampling velocity into the impactor nozzle (fixed by the choice of Nozzle Diameter and Impactor Flow Rate).

3.4.9 Quality Control

The following criteria are used to determine the acceptability of test results. Criteria 1 and 2 relate to the test series in general, whereas criteria 3 through 19 relate to the individual impactor runs.

General Test Criteria

(1) Blank Impactor Gains: A blank impactor run is mandatory in order to demonstrate the suitability of the selected substrate material. The maximum recommended range in the substrate weight changes for this blank run is 0.25mg.

(2) Minimum Number of Runs: It is recommended that seven (7) sets of traverses (multiple runs synthesizing a complete traverse) be performed. The minimum number of traverses that may be used to characterize a condition is three (3).

Criteria for Individual Impactor Runs

(3) Reproducibility of Control Weights: The control weights used in the operation of the analytical balance should be reproducible to within ±0.05 mg. The precision associated with the stage weight gains is determined by the reproducibility of the control weights.

(4) Reynolds Number Limit: The combination of selected jet stage and impactor flow rate must be such that Reynolds numbers are greater than 50. Reynolds number greater than 200 are desirable.

(5) Bounce Prevention: The combination of selected jet stage and impactor flow rate must be such that the product of the jet velocity (V) and aerodynamic stage cut point (D_{50}) does not exceed the following values:

Bare Metal Substrate:	$V \cdot D_{50} < 5$ μm-m/s
Fiber Mat Substrate:	$V \cdot D_{50} < 15$ μm-m/s
Greased Substrate c/l:	$V \cdot D_{50} < 25$ μm-m/s

(6) In-situ Sampling: Extractive sampling into an impactor is not permitted, even when heat traced lines are used and the impactor is placed in a heated oven. The nature of the problem is that excessive particulate losses occur in the extractive probe. The ability of an extractive probe to remove particles of a given size is dependent on flow rate, tube diameter, number of bends, and a host of other factors. Size selective losses occurring in the probe invalidate the data from the impactor.

(7) Straight Nozzles: Only straight nozzles may be used. Method 5 type goose neck (button hook) nozzles may not be used. The impactor must either be rotated into the gas stream so that a straight nozzle can be used or a right angle precollector should be used to permit the impactor to be operated perpendicular to the direction of the gas flow.

(8) Minimum Nozzle Diameter: Obviously to avoid bias, the nozzle diameter should be larger than the diameter of the largest particle which might be expected to be present. A problem associated with the use of small nozzles is pluggage of the nozzle by large particles. For this reason, 1.4 mm is recommended as a practical minimum nozzle ID.

(9) In-situ Heating: If the stack temperature is above 347°F (175°C), sampling may usually be performed at stack temperature. At stack temperatures less than this limit, it may be necessary to heat the impactor to at least 18°F (10°C) above the stack temperature by the use of heaters wrapped around the impactor to avoid condensation problems. The decision to externally heat the impactor depends primarily on the properties of the flue gas. Thus, high moisture stacks or high levels of H_2SO_4 or other condensible vapors may require in-situ heating of the impactors. A postrun visual examination of the impactor substrates will reveal the presence or absence of condensation problems.

(10) Warm-Up Requirement: Warm-up times should be 45 minutes to one hour. Shorter times may result in condensation occurring on various surfaces of the impactor.

(11) Minimum Run Time: The shortest permissible run time is 60 seconds. A desirable minimum run time is three minutes. If high particulate loadings result in run times shorter than 60 seconds, a lower flow rate or a different sampling device should be used.

(12) Leak Tests: The impactor must satisfy both the Pretest Hot Leak Test criteria and the Post-Test Hot Leak Test criteria given in the protocol.

(13) Anisokinetic Sampling Limits: At each traverse point sampled by a given impactor, the point velocity (υ_i) must be within ± 20% of the inlet velocity (υ) for the impactor.

(14) Nozzle Inspection: The nozzle must pass the Post-Test nozzle damage visual check.

(15) Substrate Inspection: When the impactor is unloaded, the stage catches are inspected to see if overloading, scouring, bounce, condensation, handling losses, etc., have occurred such that the data is compromised or invalidated. The shape of the deposits will provide some indication of whether or not bounce or reentrainment occurred during the run. An acceptable velocity through the jets usually results in a well-defined, cone-shaped pile of particulate matter while an excessive jet velocity yields a diffuse deposit. In extreme cases virtually none of the particles will be collected directly under the jets. Reentrainment is also more likely to occur at higher sampling flow rates. Streaks of particulate radiating out from the deposits may indicate that blow-off occurred and clumps of agglomerated material on the inlet surfaces of the jet plates almost certainly indicate that blow-off has occurred.

In addition to visual inspection, reentrainment due to stage overloading can be detected by running two otherwise identical tests for different sampling durations. If the size distribution measured in the longer run shows a pronounced bias toward smaller particles, overloading and reentrainment should be suspected. The operator must be aware, however, that substrate weight changes due to chemical reaction will not necessarily be the same for different sampling periods. Additional blank runs may be needed to resolve any doubts caused by possible substrate reactions.

(16) Isokinetic Requirements: The calculated average percent Isokinetic (I) for a given run must satisfy the following:

$$75\% \leq I \leq 125\%$$

(17) Maximum Stage Loadings: Excluding the precollector and filter, the individual substrate catch should not exceed 15 mg. If this limit is exceeded one runs a risk of overloading the substrate. The actual point where overloading occurs depends on the design of the impactor used, the type of substrate

material selected, and the properties of the material collected. A postrun visual examination may reveal visual evidence of overloading. Other tests include unrealistic filter weight changes and microscopic examination of the filter for the presence of large particles.

(18) Blank Substrate Weight Changes: The recommended range in weight changes for the blank substrate is 0.25 mg (or 10% of the expected weight change for the loaded substrates). The weight change of the blank substrate provides a cumulative measure of all balance errors (drift in the analytical balance), handling losses, flue gas-substrate interactions, etc., that might impact the weight change determinations for this impactor run. The change for each run should be compared to the grand average of all other blank substrates ("Blank" Impactor Run and blank substrate from each real run). Any given run is suspect if its blank shows a weight change significantly different (an outlier) from this grand average. Relatively large weight changes can be tolerated if they are uniform and reproducible from stage to stage and from one blank run to another. In the latter case, the grand average of the blank weight changes is substracted from the measured particulate catch weights as a background correction.

(19) Blank Filter Weight Change: Same criteria as (18) above except that the criteria are applied to the set of all blank filter weight changes rather than the set of all blank substrate weight changes.

(20) Control Runs: Control runs are recommended as a means of quantifying any substrate weight changes caused by faulty handling procedures. Although mechanical losses are not as likely to be a factor with greased foils as with fiber mats, control runs are suggested with either. To perform a control run, an impactor is loaded as for a regular run. The inlet and outlet are plugged and the impactor is carried to the sampling site. The impactor is not operated, but is kept at the sampling site until the actual run is completed. Then the control is carried back to the laboratory and unloaded in the same way as the impactors for the regular runs. Every aspect of the treatment of the control is the same as that of a real run except that it is not operated in the stack. If the substrate loses or gains more than an average of 0.05 mg, additional care must be taken to improve the handling and/or weighing procedures.

(21) On-Site Post Test Weights: At least one post test dry weight of each substrate should be recorded on site. If possible, second weighings should also be performed in the field. Second weighings of every substrate may be avoided by performing second weighings on a random selection of 10 to 20 percent of the substrates. If the first weight in each case is reproduced to within 0.05 mg, the first post test weighing may be accepted as the final dry weight of all the substrates.

3.4.10 High Concentration Sampling Situations

Most impactors are designed for sampling at relatively low concentration outlets, downstream of particulate control equipment. Consequently many of these impactors are not suitable for sampling upstream of control equipment where the particulate concentrations may be as much as 10,000 times greater

than at the outlet. Some impactors permit the operator to select from multiple stages, permitting the impactor to be configured for low flow rates. If the concentration is still so high that unrealistic sampling times (less than 60 sec.) must be used to avoid overloading one has the option of using the EPA/SoRI designed Five Series Cyclone Set described in Attachment 2 of the Project Final Report. The cyclone procedures described in Attachment 2 focus on obtaining size segregated samples for chemical analysis but the same equipment may also be used to obtain sizing information. The major modification to the cyclone operating procedures is the requirement of gravimetric analysis of the cyclone catches. This analysis is not specified in the Task 2 document because the additional handling can compromise the chemical integrity of the collected samples (particularly for organics) and is unnecessary for obtaining the chemical information. In general, if one desires both sizing and chemical information from the cyclones, any given run must be dedicated to either sizing information or chemical information and handled accordingly.

3.4.11 Wet Stacks, Condensibles, and Supplemental Heating

In sampling situations where the process stream contains entrained moisture or is near the dew point of some condensible vapor, one must first define the measurement objectives. That is, are they to: (1) characterize only the particulate to be released to the atmosphere or (2) characterize both the particulate and entrained liquid/ condensibles present in the flue. If the former is desired, as is normally the case, one must provide supplemental heating to the impactor to prevent condensation from occurring in the impactor and to reevaporate entrained liquid droplets that would be evaporated in the downwind plume. Heat is usually supplied either by means of a heating pad properly sized for the impactor/precollector or by lengths of electrical heating tape.

The temperature of the sample gas exiting the impactor should be monitored by a thermocouple exposed to the sample gas flow immediately downstream of the final filter, but the heating elements should be controlled by a second thermocouple between the impactor and the heater. A setting should be selected for this second thermocouple that will not damage the impactor or heater but will raise the temperature of the exit gas to about 20°F (as monitored by the first thermocouple) above the stack gas temperature.

If one wishes to characterize both the particulate and entrained liquid/ condensibles, many modifications are necessary. Generally, a specially designed sampler is used. The Brink impactor using deep cups, blotter type substrates, and operated in an upright position (top entry for horizontal ducts with a special 180° turn-around fitting for attaching the impactor to the probe) has been used for this purpose. Gravimetric analysis can then be performed on the wet substrates or chemical analyses can be performed for a tracer whose concentration in the original liquid is known.

3.5 Data Analysis

After obtaining a sample using a cascade impactor the data must be reduced to obtain the desired size distribution from the stage weights, sampling information, and hardware specifics. This information is used to obtain the size distribution in both differential and cumulative forms using the D_{50} method of data analysis.

The D_{50} of a stage is the particle diameter at which the stage achieves 50% efficiency: half of the particles of that diameter are captured and half are not. The D_{50} analysis method simplifies the stage collection efficiency curve by assuming that a given stage captures all of the particles with a diameter equal to or greater than the D_{50} of that stage and less than the D_{50} of the preceding stage. Thus, for the purpose of constructing a size distribution, particles collected on a specific stage are assumed to have diameters between the D_{50} of that stage and the D_{50} of the stage immediately upstream of it. The typical or average size of the particles collected by a stage is generally taken to be the geometric mean of the stage D_{50} and that of the preceding stage. Note that there is no good way to assign a typical, or average, diameter to the material collected by the first stage or the backup filter because one of the limiting diameters is undefined for them.

The simplification described above does not take into account the shape, or slope, of the actual collection efficiency curves. It is assumed, rather, that the collection efficiency curves are step functions. Some compensation for the errors implicit in this assumption occurs as a result of the efficiency curves being rather symmetric about the D_{50}. Errors resulting from not collecting some of the particles that are larger than the D_{50} are compensated for by the collection of some particles smaller than the D_{50}. If the efficiency curves were completely symmetric and the size distribution of the aerosol being sampled were flat in the vicinity of the stage D_{50}, then the compensation would be perfect. The former is very nearly true in most cases; however, the latter is true only near modal peaks or saddle points in size distributions found in actual aerosol sources. Notice that if the stage efficiency curves were true step functions, the D_{50} method would be exact; therefore the sharper the true efficiency curves are, the more nearly exact the method becomes.

Computer models of particle collection by cascade impactors have shown that reconstruction of the input size distributions using the D_{50} method yield results of tolerable accuracy when the aerosol distributions are approximately log-normal with geometric standard deviations larger than about 1.8 (McCain, 1979). This is the case for most industrial particulate emission sources.

A number of more sophisticated data reduction schemes which use measured stage efficiency curves for deconvolving the data have been proposed. However, inaccuracies in both the measured calibration curves and in the data from actual sampling runs cause serious difficulties in the application of all such methods proposed to date. Because they are not advanced enough to give reliable results at present, the D_{50} method is recommended and is the only one that will be described here.

3.5.1 Calculation of Stage D_{50} Values

The basic equation that defines the impaction behavior of a given stage of a cascade impactor is:

$$D_{50} = \left(\frac{18\ \mu\ D_j \psi_{50}}{C \rho_p \upsilon_j}\right)^{1/2} \qquad (3\text{-}6)$$

where D_{50} = diameter of a particle having 50% probability of impaction on the stage, cm

μ = viscosity of gas passing through the impactor jet(s), poise

D_j = diameter of impactor jet, cm, or, alternatively, the width, W_j, of slot in a slotted impactor, cm

ψ_{50} = inertial impaction parameter determined by calibration, dimensionless

C = Cunningham slip correction factor, dimensionless (given below) (calculated using upstream conditions)

ρ_p = density of particle, g/cm^3

υ_j = mean velocity of gas through an impactor jet, cm/sec (calculated using upstream pressure)

and

$$C = 1 + \frac{2\ell}{D_{50}}\left[1.23 + 0.41\ \exp\left(\frac{-0.44\ D_{50}}{\ell}\right)\right] \qquad (3\text{-}7)$$

where ℓ = mean free path of air molecules at impactor stage (at upstream conditions), cm

$$= \frac{0.7923\mu}{P}\ \sqrt{T/MW}$$

P = gas pressure at stage inlet, cm Hg

T = gas temperature, °k

and MW = wet molecular weight of the gas

The Stokes diameter of a particle, as defined by equation 3-6, is of interest for most applications. However, at times, for example for PM_{10} purposes, data must be expressed in terms of the aerodynamic diameter, defined as the diameter of a sphere having unit density and the same settling velocity as the particle of interest. In order to calculate the D_{50} of an impactor stage on an aerodynamic basis, ρ_p is set equal to 1.0 g/cm^3 and equation 3-6 becomes-

$$D_{50} = \left(\frac{18\psi_{50}\mu D_j}{C\, v_j}\right)^{1/2} \qquad (3\text{-}8)$$

The values of ψ_{50} for each stage of the impactor can be found by using the calibration procedures outlined in Section 2 or may be calculated from theory. Then, since C is dependent on particle size, the D_{50} can be calculated using an iterative solution of equations 3-6 and 3-7 or 3-8 and 3-7.

3.5.2 Single Run Data Analysis and Presentation

The true particle-size distribution of almost any particle-laden gas stream (outside the laboratory) is a smooth and continuous curve. As impactors have a finite number of stages, they break this continuous particle-size distribution into a series of discrete sets of particulate matter in separate size intervals. In actuality, these intervals overlap somewhat, but they are not generally treated as doing so. If the widths of the intervals are large compared with the ranges of overlap, the errors introduced by ignoring the overlaps are small. The object of impactor data analysis is to transform the discrete data into a good approximation of the real, continuous distribution.

Anomalies are introduced into the reconstructed size distributions obtained using the D_{50} method if the D_{50}'s of two successive stages are close enough to one another that the efficiency curves overlap significantly. In such cases, the second (downstream) stage receives an aerosol whose concentration varies rapidly with diameter within the vicinity of its D_{50}, violating the basic assumption of the D_{50} method. It can be shown that the effect of the overlap is a positive bias in the apparent concentration of particles in the nominal size range of those caught on the second of the two stages. Thus, the differential distribution is biased high in the interval between the D_{50}'s of the two stages, and is correspondingly biased low in the interval covered by the next successive stage. As an illustration, consider two successive stages whose D_{50}'s are infinitesimally close to one another. The mass which should be collected between the two D_{50}'s to properly represent the aerosol size distribution would then also be infinitesimally small. However, the second of the two stages will in fact collect an appreciable amount of particles whose diameters lie in the region where the collection efficiency values of the two stages lie between 5 and 95 percent. Particles in this size range have a significant probability of passing the first stage and being captured by the

second. For the case of D_{50} values which are essentially identical, the mass on the second stage has the effect of introducing an apparent discontinuity in the reconstructed cumulative distribution or a spike in the differential distribution. In practice, one can avoid the problem introduced by this effect by combining the mass collected by the second of the two closely spaced stages with that of the stage immediately following it and omitting the second stage from the analysis. A good working practice is to maintain the ratio of successive D_{50}'s at values of 1.4 or greater.

It is assumed for the purpose of analysis that all of the material caught on an impaction stage consists of particles having aerodynamic diameters equal to, or greater than, the D_{50} for that stage, and less than the D_{50} for the next higher stage. For the first stage (or precollector), it is assumed that all of the particles caught have aerodynamic diameters greater than, or equal to, the D_{50} for that stage (or precollector), but less than the maximum particle size. When possible, the maximum particle size should be measured, for example, with an optical microscope. If this is impossible, an arbitrarily large value of 1000 μm or larger should be used for uncontrolled sources and a value of about 100 μm for controlled sources.

Data should be presented as both differential and cumulative particle-size distributions as described in the following discussion.

3.5.3 Differential Particle-Size Distributions

Since the true particle-size distribution is continuous, the mass of material with particle diameters between D and D + dD can be represented by dM. Then the integral

$$\int_{D_1}^{D_2} \left(\frac{dM}{dD}\right) dD \qquad (3\text{-}9)$$

yields the total mass made up of particles with diameters between D_1 and D_2.

Many cascade impactors are designed so that the relationship between successive stage D_{50}'s is logarithmic. Further, many natural aerosol size distributions are very nearly log-normal. That is, the distributions are gaussian if the logarithm of diameter is used as the independent variable. For these reasons, and to minimize graph scaling problems, the differential particle-size distributions are plotted on log-log or semi-log paper with dM/dLogD as the ordinate and Log D as the abscissa. The mass of the material on stage "n" is designated by ΔM_n and is, in approximation, the mass of particulate matter with particle diameters between $(D_{50})_n$ and $(D_{50})_{n-1}$. The Δ(Log D) associated with ΔM_n is $\text{Log}(D_{50})_{n-1} - \text{Log}(D_{50})_n$. Note that diameters decrease as "n" increases. Using these approximations, the derivative term associated with stage "n" is defined as follows:

$$[dM/dLogD]_n \simeq \frac{\Delta M_n}{\Delta(\text{Log}D_{50})_n} = \frac{\text{mass on stage "n"}}{\text{Log}(D_{50})_{n-1} - \text{Log}(D_{50})_n} \qquad (3\text{-}10)$$

Plotting this approximation of dM/dLogD versus Log D results in a histogram. From such a histogram, the total mass of particles with diameters between $(D_{50})_i$ and $(D_{50})_j$ can be calculated as the sum:

$$\text{Mass} = \sum_{k=i}^{j} \frac{\Delta M_k}{\Delta(\text{Log } D_{50})_k} \Delta(\text{Log } D_{50})_k \qquad (3\text{-}11)$$

where "k" takes on values corresponding to the discrete increments of the histogram.

If an impactor with an infinite number of stages having step function efficiency curves were available, the histogram would approach a continuous function, the $\Delta(\text{Log } D_{50})$ terms would approach d(Log D), and the mass between D_m and D_n could be calculated as:

$$\text{Mass} = \int_{D_m}^{D_n} \left(\frac{dM}{d(\text{Log } D)}\right) d(\text{Log } D) \qquad (3\text{-}12)$$

Such an impactor does not exist, but the histogram can be plotted as a smooth curve by assigning some average of $(D_{50})_{n+1}$ and $(D_{50})_n$ to the $\Delta M/\Delta(\text{Log } D_{50})_n$ term and drawing a smooth curve through the resulting points. The geometric mean of the D_{50}'s is generally used. This curve is then a continuous function approximating the actual particle-size distribution. Note that the area under the curve in a given size range is equal to the mass of the particulate matter in that interval. Such a curve is needed to calculate fractional collection efficiencies of control devices if the D_{50}'s differ for inlet and outlet measurements. To normalize the differences in the masses of samples collected by various instruments, the mass on each stage is usually divided by the volume of the sampled gas at standard temperature and pressure, yielding concentration units. Figure 3-22 illustrates a typical dM/dLogD plot. The accuracy of the approximation described above is limited by the number of data points and by neglecting the non-ideal behavior of the impactors, especially overlapping collection efficiencies for adjacent stages.

An alternative method of calculating the differential particle size distribution is to measure the slope of the cumulative mass loading curve (described below) at selected intervals and plot this slope versus the corresponding particle size.

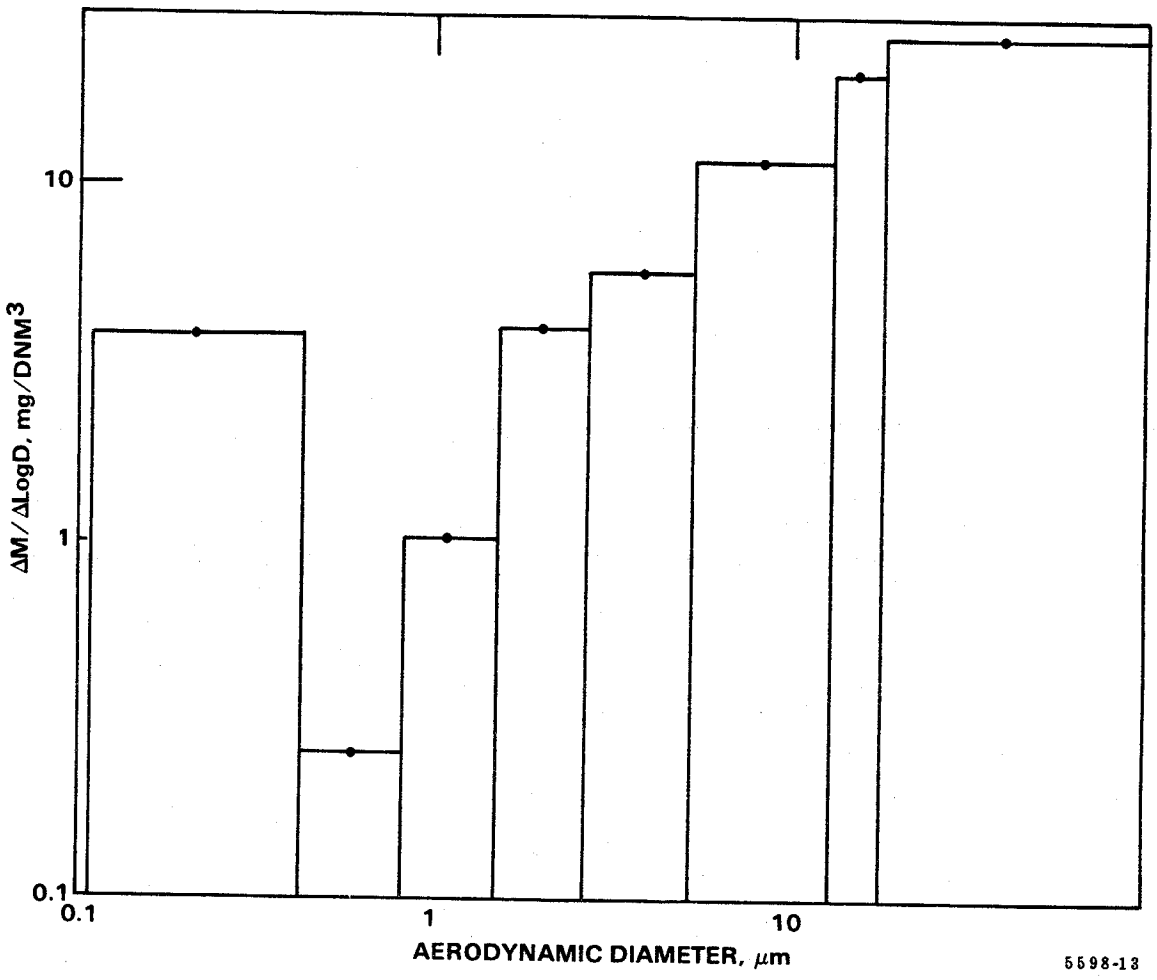


Figure 3-22. Differential size distribution estimated directly from the stage weights and $D_{50's}$ of an impactor run.

A differential number distribution can also be derived. Since ΔM_j is the mass per unit volume for stage j then we can define ΔN_j as the number of particles per unit volume for stage j. Now ΔM_j and ΔN_j are related by the equation $\Delta M_j = \Delta N_j \times M_p$, where M_p is the average mass of the particles collected on the stage. Dividing both sides of the equation by $M_p \times \Delta LogD$ yields:

$$\frac{(\Delta M/\Delta LogD)_j}{M_p} = \frac{\Delta N_j}{(\Delta LogD)_j} \qquad (3\text{-}13)$$

Where $M_p = \rho_p V_p$ and ρ_p is the assumed density of the particle and V_p is the average volume of one particle on a given stage:

$$M_p = \frac{\pi \rho_p (GMD)_j^3}{6} \qquad (3\text{-}14)$$

Therefore:

$$(\Delta N/\Delta LogD)_j = 6\ (\Delta M/\Delta LogD)_j / \pi \rho_p (GMD)_j^3 \qquad (3\text{-}15)$$

3.5.4 Cumulative Particle-Size Distributions

Two forms of cumulative distributions are commonly used - cumulative concentration and cumulative percentage. These are generated, respectively, by summing the concentrations of particles smaller than the D_{50}'s of successive stages or by summing the percentages of the total concentration smaller than the successive D_{50}'s. Distributions in this form are conventionally plotted commencing at the smallest diameter for which data was obtained and progressively summing to the larger sizes.

Cumulative distributions do have some disadvantages compared to differential distributions. An error in a stage weight is propagated forward throughout the remainder of the distribution in a cumulative analysis, but is isolated by the differential approach. Also the differential method need not involve the use of data for sizes outside of the range over which the sampler provides size resolution and so is useful in comparing results obtained with impactors with those obtained from instruments which cover only restricted particle size intervals (e.g. optical particle counters). Cumulative distributions are also not amenable to making direct comparisons of concentrations at selected sizes as can be done with differential distributions.

Cumulative Concentration Format

A cumulative concentration particle-size distribution is shown in Figure 3-23. Distributions in the cumulative concentration format are formed by first calculating the concentrations for each size fraction provided by the sampler and successively summing these. If the conventional format is followed and the

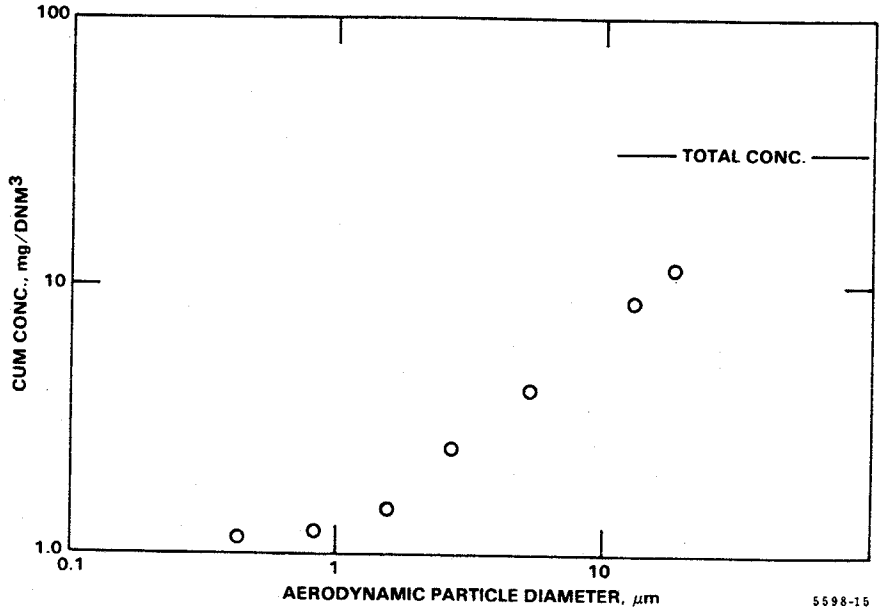


Figure 3-23. Particle size distribution on a cumulative concentration basis estimated directly from the data of an impactor run.

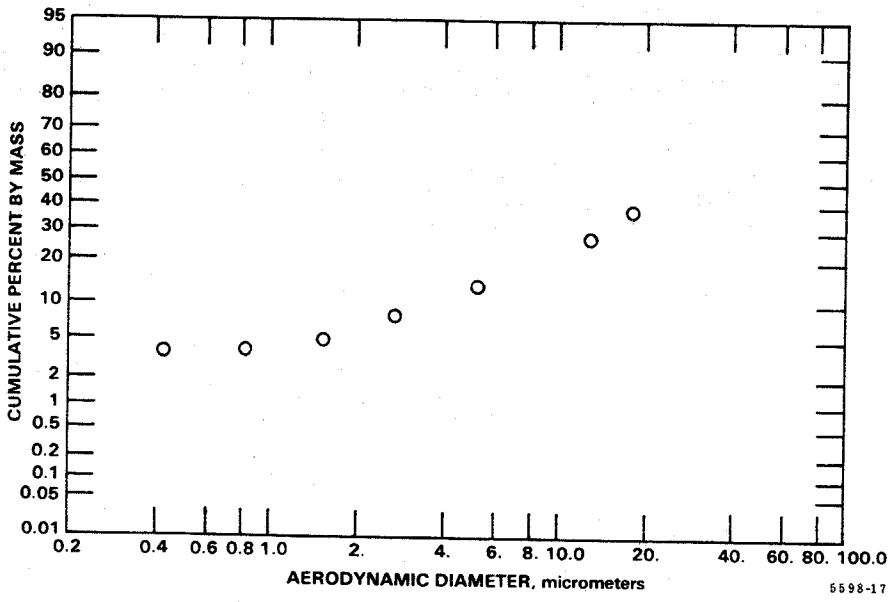


Figure 3-24. Typical particle size distribution on a cumulative percentage by mass basis as measured with a cascade impactor.

summation begins at the smallest D_{50}, any error in the sample collected on the backup filter is propagated throughout the entire presentation. Because the backup filter catch is affected to a far greater extent than the remaining stage catches by particle bounce and reentrainment, it is especially important that the magnitude of these effects be held to a minimum if the cumulative distributions are to be kept relatively unbiased. Summing from the large particle end of the size spectrum does not necessarily rid the distribution of bias since the measured concentrations of large particles are susceptible to bias from, among other things, the inability to maintain true isokinetic sampling conditions (because of the requirement of fixed sampling flow rates). The small particle end of the size spectrum is selected for the beginning of the summation because in most instances the larger particles dominate the distribution and the addition of the smaller particles to the larger would be undetectable in the presentation. Note that it is possible to present data in a form of cumulative concentration format in the absence of information regarding concentrations at one extreme of the distribution.

The value of the ordinate at a given D_{50} would be:

$$\text{Mass concentration smaller than } (D_{50})_k = \sum_{i=0}^{k-1} C_i \qquad (3\text{-}16)$$

where i = 0 corresponds to the filter,
i = k corresponds to the selected stage,
C_i = concentration determined from the stage i particulate catch,
N = total number of stages (including the precollector).

This equation requires that the stages be counted upward from the final filter. There is no $(D_{50})_0$ since the "0" stage corresponds to the backup filter. $(D_{50})_1$ is the cut-point of the final impaction stage.

Cumulative Percentage Format

A cumulative percent particle-size distribution is shown in Figure 3-24. Many aerosols have particle size distributions which follow, or can be approximated by, the "Normal" or Gaussian function if the logarithm of the particle diameter is used as the independent variable. Such distributions, called log-normal distributions, can be characterized or described by three parameters: a normalizing constant which defines the total concentration, and two constants which define the location and shape of the distribution. Generally, the mass median diameter and the geometric standard deviation are used for the latter two parameters. The mass median diameter, or MMD, locates the diameter about which the distribution is centered and is the diameter at which half the particulate mass is contained in particles having smaller diameters and half in those which are larger. The geometric standard deviation, or σ_g, defines the spread of the distribution and is defined by ratios of the median diameter and the plus and minus one sigma diameters in the log-normal function. It is approximately equal to D(84%)/MMD and/or

MMD/D(16%), where D(84%) and D(16%) are the diameters below which sizes one finds respectively 84% and 16% of the particle mass.

Size distribution presentations on a cumulative percentage basis are formed as the sums of the percentages of the total catch collected by each stage of the sampler. When plotted, they are usually displayed on special log-probability paper as in Figure 3-24, with the logarithmic axis used for particle diameter, and the "probability", or percentage, axis for the cumulative percentage. True log-normal distributions form straight lines when plotted on this paper, making estimation of the mass median diameter and geometric standard deviation a simple task. Deviations of a distribution from the log-normal form will result in curvature or slope changes in the plot.

Disadvantages of the cumulative percentage format are that knowledge of the complete size distribution is required to form it, and an error in the measured concentration in any size interval is propagated throughout the entire presentation. It should also be remembered that a distribution presented in a cumulative percentage format is incompletely specified, as it contains no information with regard to absolute concentrations. In order to make full utilization of the data possible, the total concentration should be specified in the plot legend.

The value of the ordinate at a given D_{50} would be:

$$\text{Mass percent smaller than } (D_{50})_k = \frac{\sum_{i=0}^{k-1} m_i}{\sum_{i=0}^{N} m_i} \qquad (3\text{-}17)$$

where i = 0 corresponds to the filter,

i = k corresponds to the stage under consideration,

m_i = mass collected on stage i, and

N corresponds to the total number of stages.

Again, this equation requires that the stages be counted upward from the final filter.

3.5.5 Combining Data from Multiple Runs

The previous parts of this section deal with the analysis and presentation of data from a single impactor run (sample). However, in most cases a number of runs will be made at each source and condition tested, and the data from these several runs must be combined or averaged to produce the desired final distribution. These runs may represent repeated samples taken at a common location, or they may be samples taken from a number of locations across a duct to insure that a representative result is obtained in circumstances where

stratification may or does exist. Even under the best of circumstances, combining data from multiple samples can be difficult. Differences in sampling flow rates, temperatures, and perhaps in the hardware used from one run to another will result in variations in the cut diameters (D_{50}'s) for any one impactor stage from one run to the next at any location. Because of these differences in stage D_{50}'s, it becomes improper to simply average the results for individual stages or to directly compare them for calculating control device efficiencies. The solution to the problem is to generate a continuous analytic function (or series of functions) which fit the measured results for each run. Interpolation using these functions permits one to express the results of all the runs at a common set of selected diameters. Once the data are adjusted to a common diameter basis, it becomes a simple matter to average and compare runs.

Two approaches have been tried in generating analytic expressions fitted to measured data. In one approach, least squares or other optimizing procedures are used to fit any one of a number of common distribution functions to the data (e.g. the log-normal function). However, except in rare instances, these functions are only approximations to the real distributions and may be poor approximations at that. The more widely favored and used approach is to make a piecewise continuous spline fit to the data. Usually such a fit is made to one of the forms of the cumulative distribution because in the limit the stage cuts become true step functions and, fits to the cumulative distribution become exact. In any case, such techniques provide useful interpolation methods, and, by making use of some boundary conditions, can be used to make reasonable extrapolations beyond the size range spanned by the largest and smallest D_{50}'s of the impactor.

A spline technique was recommended for use by the ARB and is implemented in the computer data reduction package detailed in Appendix A of the procedures document (it is impractical, laborious and time consuming to apply the technique using manual calculations). The technique is a modification of one proposed by Lawless (1978) in which a cubic spline fit is made to the cumulative percentage form of the measured distribution in log- probability space. Modifications have been made to Lawless's technique to insure that no negative slopes are generated and to force continuity in slope in the extrapolation regions beyond the span of the impactor D_{50}'s. The results of the fit to the cumulative percentage data points are converted back to a concentration basis for the remaining steps. Once obtained, the analytic expression(s) for the fit can be used to generate values of the cumulative distribution at user selected particle sizes and can be differentiated to obtain values of dM/dLogD at any desired diameter.

An alternative spline fit procedure was developed by Johnson et.al. (1978) as a part of the development of CIDRS (Cascade Impactor Data Reduction System) for the US EPA. In the EPA CIDRS the fit is made in log-log space to the cumulative concentration form of the distribution. Modeling of impactor performance in sampling unimodal and bimodal particle size distributions and comparisons of the resulting apparent distributions produced by the EPA CIDRS with the originals showed excellent agreement within the span of the impactor D_{50}'s and fair agreement in extrapolations to beyond a factor of two in diameter from the limits of the measurement range (McCain et.al., 1979). Similar tests of the EPA CIDRS by Smith et.al. (1982) showed that the maximum

errors which might be expected in extrapolations of cumulative concentrations to diameters of about twice the D_{50} of the first impactor stage were about 15% and typical errors would be 5% or less. Because most aerosol size distributions are approximately log-normal, the curvatures of the distribution plots are much less radical in log-probability space and consequently easier to fit without generating artifacts; therefore, the cubic spline fit in log-probability space was selected for use by CARB. Experience in fitting the same data by both the Lawless and SoRI techniques has shown good agreement between the two when the data are well behaved and superior performance by the log-probability fit when the cumulative concentration curve showed extreme curvatures. Therefore, the errors associated with the extrapolations made using the Lawless method are expected to be no worse than comparable to those from the EPA CIDRS technique.

Averages of size distribution data are generally desired in both differential and cumulative forms together with measures of the scatter in the data (e.g., variances and/or confidence limits). Having obtained the spline fits, it becomes a simple matter to obtain average values of dM/dLogD and associated variances for a standard set of user selected diameters. In addition, standard statistical tests for outliers can be used to flag and, if desired, remove values from the averaging process if they deviate too greatly from the rest of the data.

The situation becomes more complicated when averages for the cumulative forms of the distribution are sought. Direct averaging of data in the cumulative percentage form is quite inappropriate because all information regarding relative concentrations among the runs is lost in the cumulative percentage distribution form. The average cumulative percentage distribution must instead be generated from the average cumulative concentration. Because errors in values for single impactor stages are propogated forward from the D_{50} of the stage throughout the remainder of the distribution, valuable information from stages other than the one with the bad data will be lost if the cumulative distributions are averaged directly with removal of outliers. On the other hand if direct averaging is used without omitting erroneous values detected through outlier analysis, the errors are incorporated in the final results. In order to circumvent these problems, average cumulative distributions are better constructed by numerically integrating the averaged differential distribution. This results in the omission of data from the averaging process only for sizes in the immediate vicinity of the range covered by the stage(s) for which the values are suspect. Variances for the resulting points on the cumulative distribution curve are estimated by using the fact that the variance in the sum of two quantities is equal to the sum of their individual variances.

Another complication is introduced if the velocity profile across the duct from which the samples are taken is not uniform. The actual transport rate of particles, R_i, of any given size through the duct is given by the expression

$$R_i = \text{area} \int C_i \cdot \upsilon dA \qquad (3\text{-}18)$$

where C_i = the local particle concentration for size i,

and υ = the local gas velocity.

This integral is normally approximated by the sum:

$$R_i = \sum_n C_{i,n} \cdot \upsilon_n \cdot A_n \qquad (3\text{-}19)$$

where A_n = partial duct area represented by a particular sample,

$C_{i,n}$ = the concentration measured at point n,

and υ_n = the velocity at point n.

(Note that this is exactly analogous to the manner in which emission rates are measured using Methods 5 and 17.) Therefore, the correct procedure for combining data from runs made at several different locations in the duct cross section is to construct averages which are weighted by the velocities at the sampling points and by the cross sections for which the velocities are representative. Provision for making these weighted averages is made in the computer data reduction package provided as a part of the contract.

3.5.6 Calculation of the Fractional Efficiencies of Control Devices

The efficiency with which a control device collects particles of a given size is given by the expression:

$$E = 1 - (C_o/C_i) \qquad (3\text{-}20)$$

where

C_o = the outlet concentration at that size

and C_i = the inlet concentration at that size

with both concentrations being expressed at the same gas conditions. Since $(dM/dLogD)_i$ represents the concentration of particles having diameter, between D_i and D_i + dLogD, respective inlet and outlet values of dM/dLogD may be substituted for the concentrations in the equation. These values can be obtained from the spline fits if data from individual runs are to be compared, or from averages of the differential distributions if data from multiple runs are to be compared.

3.5.7 Cascade Impactor Data Reduction System (CIDRS)

Although it is possible to reduce data obtained from cascade impactors by hand or with calculators, the number of calculations which must be done to treat the data from just one impactor run make hand calculations impractically laborious. When the treatment of data from multiple runs is considered it

becomes obvious that a computer is required. In March 1978 a system of programs known by the acronym "CIDRS" (for Cascade Impactor Data Reduction System) was published for this purpose by the US EPA. CIDRS was written in Fortran for use on large "main-frame" computers and has been adapted since for use on some minicomputers. Denver Research Institute released an adaptation of CIDRS written in BASIC for the TRS-80 micro-computer in March 1980. The system described here, Apple CIDRS, is an updated and expanded adaptation of the TRS-80 CIDRS, written in BASIC for the Apple II micro-computer series. With some effort, the program could be adapted to any other micro-computer which is programmable in one of the variants of Microsoft BASIC.

The CIDRS package consists of a series of programs which together provide the capabilities to:

1) Calculate and store the values of needed ancillary data such as dry gas composition and moisture content of stack gases (Methods 3 and 4).

2) Reduce velocity (pitot) traverse data (Method 2) and aid in the selection of sampling flow rates and nozzle dimensions.

3) Generate files containing the hardware specifics on the impactor configurations used in sampling for later use in calculating stage D_{50}'s.

4) Reduce the data from individual impactor runs and generate size distribution information from that data at a set of standard conditions for a standardized array of particle sizes.

5) Combine and appropriately average the results from multiple sample runs obtained at a single source.

6) Calculate the fractional efficiencies of control devices from samples obtained at the control device inlets and outlets.

7) Plot the size distributions and fractional efficiencies obtained above.

In addition, programs are also provided to facilitate program selection, for carrying out disk file "housekeeping" chores, defining orifice constants for use in flow rate calculations, and for reducing Method 5 and Method 17 data.

Briefly, the programs in CIDRS relating to single impactor run data analysis are:

MPPROG - This is the main program of the system. It accepts and reduces the raw data from single impactor runs. The program calculates impactor stage D_{50}'s, particle concentrations for each stage, provides some information for quality control and data validation, calculates log-normal distribution parameters based on a least squares best fit to the measured size distribution, and generates size distribution information for a set of standardized particle

sizes through a spline fit and interpolation/extrapolation procedure. Raw data may be saved on disk for subsequent reuse and the final results can also be saved for plotting or to be combined with data from other runs.

ORSAT - Accepts data from Orsat analyses, calculates excess air for combustion processes, and writes the gas composition data to disk for later use by MPPROG.

METH4 - Reduces data from Method 4 moisture content sampling and writes the results to a disk file for later use by MPPROG. The file value for moisture content becomes the default value used in reducing impactor data, but it can be altered in MPPROG.

DEF/IMP - This program builds files containing specific hardware information on the impactor configurations used in sampling. Information on the type of impactor (round or rectangular jets), number of stages, the number and sizes of the jets on each stage, calibration values of $\sqrt{\psi_{50}}$ for each stage, and jet to plate spacing for each stage must be entered. The information in these files is used by MPPROG for calculating the stage D50's.

DEF/ORI - MPPROG permits the impactor flow rate and gas volume sampled to be calculated from data obtained with dry gas meters or from orifice meters at the users option. This program generates files of orifice calibration information for use by MPPROG if the flow rate is to be calculated from orifice meter data. It also calculates values for $\Delta H@$ for use in setting flow rates during sampling.

The programs in CIDRS related to combining data from multiple runs are:

STATIS - A program for averaging data from multiple runs made under similar conditions. Simple averages of the differential forms of distributions are made with tests for and rejection of outliers being made at the user's option. The average differential distribution is then integrated to obtain the average distribution in the cumulative forms. Standard deviations and 90% confidence limits are calculated for all forms of the distribution. Provision is also made for correcting the data for errors arising from anisokinetic sampling if the user so desires. The results can be written to disk for later plotting and for use in calculating fractional efficiencies of control devices.

SYNTRAV - Similar to STATIS but performs velocity weighted averaging for properly combining results obtained in ducts having skewed (or non-uniform) velocity distributions.

EFFICIENCY - Calculates the fractional efficiencies of control devices from control device inlet and outlet data sets. The inlet and outlet data can be from single runs or averaged results from STATIS or SYNTRAV. If both the inlet and outlet data sets are averaged results, confidence limits for the resulting efficiencies are also calculated.

Plotting - Only screen plotting capabilities are included in the system with provision for doing "screen dumps" to dot matrix printers that have graphics capability. The actual plotting is done via a commercial machine language program, Ampergraph. The programs on the impactor run analysis disk related to plotting are:

PLOT3 - Plots data from single runs in three forms: differential, cumulative mass concentration, and cumulative percent by mass. In the cumulative forms both the original distribution generated directly from the data and the results from the spline fit are plotted.

STATPLOT - Plots the results of combining data from multiple runs by STATIS or SYNTRAV. The results are plotted in the same three forms as used in the single run plotting. Error bars representing 90% confidence limits are also shown.

EFF/PLOT - Plots fractional efficiency results from EFFICIENCY together with error bars representing 90% confidence limits,if available.

The programs related to field setup include programs for Orsat calculations, Methods 2, 4, 5 and 17 data reduction, calibration of orifice meters and dry gas meters using NBS traceable laminar flow devices, calibration of pitot tubes, and sampling setup programs for Methods 5 and 17 and cascade impactors. These are:

MTOP - Method 5/17 setup program. This program aids in selecting the correct sampling nozzle to use for Method 5 or 17 sampling and provides an alternative to the standard sampling nonograph for generating metering orifice settings by generating a table of corresponding pitot and metering orifice settings. The latter can simplify field sampling, and permits the use of non-standard metering orifices, which can be advantageous at times.

MTDR - Data reduction program for Methods 5 and 17.

IMPOP - Program for reducing velocity traverse data, selecting impactor nozzle diameters and flow rates for isokinetic sampling, selecting metering orifices for impactor sampling, and generating orifice meter pressure drop settings for impactor sampling.

PCONST - Program to calculate calibration constants for pitot tubes from comparative velocity pressures at a common location.

The programs described above all use menu selection of all options, and provide interactive prompts for data input. More complete descriptions of each of the programs, lists of all variables used, and detailed operating instructions are found in an appendix to the Procedures Manual for the Proposed ARB Particle Sizing Method.